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A novel approach to optimize management strategies for carbon stored in both forests and wood products

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ABSTRACT

We present a new approach to maximize carbon (C) storage in both forest and wood products using optimization within a forest management model (Remsoft Spatial Planning System). This method was used to evaluate four alternative objective functions, to maximize: (a) volume harvested, (b) wood product C storage, (c) forest C storage, and (d) C storage in the forest and products, over 300 years for a 30,000 ha hypothetical forest in New Brunswick, Canada. Effects of three initial forest age-structures and a range of product substitution rates were tested. Results showed that in many cases, C storage in product pools (especially in landfills) plus on-site forest C was equivalent to forest C storage resulting from reduced harvest. In other words, accounting for only forest, and not products and landfill C, underestimates true forest contributions to C sequestration, and may result in spurious C maximization strategies. The scenario to maximize harvest resulted in mean harvest for years 1–200 of 3.16 $m^3\,ha^{-1}\,yr^{-1}$ and total C sequestration of 0.126 $t\,ha^{-1}\,yr^{-1}$, versus 0.98 $m^3\,ha^{-1}\,yr^{-1}$ and 0.228 $t\,ha^{-1}\,yr^{-1}$ for a scenario to maximize forest C. When maximizing total (forest + products) C, mean harvest and total C storage for years 1–200 was 173% and 5% higher, respectively, than when maximizing forest C; and 218% and 6% higher, respectively, when maximizing substitution benefits (0.25 t of avoided C emissions per m^3 of lumber used) in addition to total C. Initial forest age-structure affected harvest in years 1–50 < 34% among the four alternative management objective scenarios, and resulted in mean C sequestration rates of 0.31, 0.10, and –0.14 $t\,ha^{-1}\,yr^{-1}$ when maximizing total C storage for young, even-aged, and old forests, respectively. Our results reinforce the importance of including products in forest-sector C budgets, and demonstrate how including product C in management can maximize forest contributions toward reduced atmospheric CO_2 at operational scales.

1. Introduction

Given concerns and projections about climate change (e.g., IPCC, 2006), there has been a proliferation of research over the last decade into forest carbon (C) inventories, forest management strategies to sequester C, life-cycle analysis of C in forest products, and avoided emissions from product substitution. In surveying the literature in preparing this paper in late 2007, we identified over 100 papers related to forest or forest products C sequestration, 80% of which were published since 2000. These include stand and forest-level C inventories (e.g., Kurz et al., 1995; Kurz and Apps, 1999; Fredeen et al., 2005; Monni et al., 2007; Neilson et al., 2007; Woodbury et al., 2007), models of C sequestration and timber production (e.g., Kurz et al., 1992, 2002; Backéus et al., 2005; Gusev and Nasonova, 2007), simulation of effects of management and climate on C sequestration by forests (e.g., Kurz and Apps, 1995; Liski et al., 2001; Harmon and Marks, 2002; Peng et al., 2002; Karjalainen et al., 2003; Meng et al., 2003; Backéus et al., 2006; Schmid et al., 2006; Neilson et al., 2006, submitted for publication; Garcia-Gonzalo et al., 2007; Seidl et al., 2007), forest products C accounting (e.g., Skog and Nicholson, 1998; Winjum et al., 1998; Apps et al., 1999; Lim et al., 1999; Skog et al., 2004; Perez-Garcia et al., 2005a), and forest products life-cycle and fate analyses (e.g., Petersen and Solberg, 2003; Perez-Garcia et al., 2005b; White et al., 2005; Lippke and Edmonds, 2006; Upton et al., 2008).

Although the C accounting guidelines for the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto protocol exclude C stored in forest products, common sense dictates that any reasonable assessment of the role of forests in global, national, or regional C cycles should include consideration of sequestration of C in forest products. This notion is prevalent in ongoing discussion toward negotiation of the second commitment period reporting rules (Höhne et al., 2007; Nabuurs et al., 2007; Schlamadinger et al., 2007). Several

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Fig. 1. Three initial age-structures for a 30,000 ha hypothetical test landbase were simulated: young (a), even-aged (b), and old (c). Area per 5-year age class is shown.

integrated analyses have indicated that a considerable proportion of C contained in forest products remains sequestered for long periods. Net C stocks stored in Canada for the forest products sector, estimated as the difference between harvest C input and total losses from the sector at 23.5 Mt C yr^{-1} for 1985–1989, contribute significantly to reduction of total net atmospheric C exchange (Apps et al., 1999). North American C stocks from Canadian wood products produced were increasing at rates of 16.14 Mt C yr^{-1} in 1990 and 21.9 Mt C yr^{-1} in 2005 (NCASI, 2007; converted from CO_2 eq.).

Perez-Garcia et al. (2005a) determined that when only forest C was accounted for, the longer the harvest cycle, the greater the amount of C removed from the atmosphere. Even if product C was included and rate of exported C exceeded rate of tree growth, conversion inefficiencies and eventual decay limited C removed from the atmosphere. Only when product substitution was included in the analysis, could forestry lead to significant reduction in atmospheric C by displacing more fossil-fuel intensive products (Perez-Garcia et al., 2005a). Although several analyses have accounted for both C in forests and products (e.g., Winjum et al., 1998; Apps et al., 1999; Lim et al., 1999; Skog et al., 2004), these have typically been at large regional or national scales. Although dependent on product conversion efficiencies and decay rates in primary use and landfills, forest products can be a significant long-term C sink (Kurz et al., 1995; Apps et al., 1999), and therefore should be included in C accounting frameworks and design of forest management strategies to increase total C storage. While numerous studies have developed methods within forest optimization models to quantify and maximize C stored in live biomass and dead organic matter (DOM) pools, none to our knowledge have simultaneously accounted for and optimized C stored in forest ecosystems, product use including landfill pools, and avoided emissions from product substitution.

In this paper, we present a modeling framework that integrates C accounting of forest living biomass, DOM, and wood products into an optimization model (Woodstock, Remsoft Spatial Planning System; Remsoft Inc., 2006). Woodstock is a flexible and widely used forest modeling tool capable of solving complex mathematical forest management problems through use of commercial linear optimization solvers or simulation modeling. Our objectives were to: (1) demonstrate a new approach to account for, and maximize, C storage in wood products within a forest optimization model; (2) apply the model to a hypothetical forest landscape to identify optimum forest management strategies that maximize four independent objectives: (i) volume harvested, C stored in (ii) the forest, (iii) wood products (lumber, paper, landfill), or (iv) forest and product C pools; and (3) evaluate effects of three initial forest age-structures and alternative product substitution rates (tonnes of avoided C emissions per m^3 of lumber used).

2. Materials and methods

2.1. Forest description and management assumptions

We constructed a hypothetical 30,000 ha forest in the Woodstock model with initial area divided equally among three natural (untreated) stand types common in eastern Canada: (1) softwood (SW), dominated (>50% composition) by spruce (*Picea* spp.) and balsam fir (*Abies balsamea* (L.) Mill.); (2) hardwood (HW), dominated by shade-tolerant yellow birch (*Betula alleghaniensis* Britt.), sugar maple (*Acer saccharum* Marsh.), and beech (*Fagus grandifolia* Ehrh.), and intolerant to intermediate tolerant hardwoods (primarily trembling aspen (*Populus tremuloides* Michx.), red maple (*Acer rubrum* L.), and white birch (*Betula papyrifera* Marsh.)); and (3) mixedwood (MW), dominated by spruce and tolerant hardwoods. We also defined three initial forest age-structures (young, even-aged, old; Fig. 1), to assess effects on management strategies to maximize harvest volume or C storage in forest and/or products.

Stand treatment interventions included clearcut (100% volume removal) and selective harvest (30% volume removal every 30 years), SW planting, and SW and MW pre-commercial thinning (PCT). Following clearcut harvest, 50% of harvested SW and MW area was assumed to regenerate in equal proportions to SW and HW, and the remaining 50% regenerate to MW; clearcut HW stands were assumed to regenerate to HW. All regenerating stands ≤ 5 years old were eligible to be planted with genetically improved high-yielding black spruce (*Picea mariana* (Mill.) B.S.P.), or alternatively, stands of SW or MW type between 10 and 15 years old could be pre-commercially thinned to promote faster diameter growth and earlier onset of merchantable volume. Selective harvest was operable in mature stands having ≥ 150 m^3 ha^{-1} of volume, with targeted removal of intolerant hardwoods, beech, and balsam fir where possible. Clearcut harvest was operable in stands having ≥ 75 m^3 ha^{-1}.

Stand projections (Figs. 2a–d and 3a–c) of merchantable volume, by product (pulpwood and sawlog) and species, were modeled using the New Brunswick Stand Management growth and yield model (STAMAN; MacLean, 1996; Erdle and MacLean, 1999). STAMAN is a diameter class empirically based stand table projection model, with tree growth and survival relationships derived from permanent sample plots. STAMAN model runs are initialized with stand tables compiled from forest inventory data (New Brunswick Growth and Yield Unit, 2002). Stand development for 250 years was simulated, including regeneration to maturity, stand decline, and sapling ingrowth dynamics. Stand projections were grouped by species composition (SW, MW, HW) and treatment (unmanaged, SW and MW PCT, SW plantation) to produce average age-dependant projections of merchantable volume by species (Fig. 2). Planted spruce treatments achieved higher stand yields than natural SW (Fig. 2d), and because of lack of

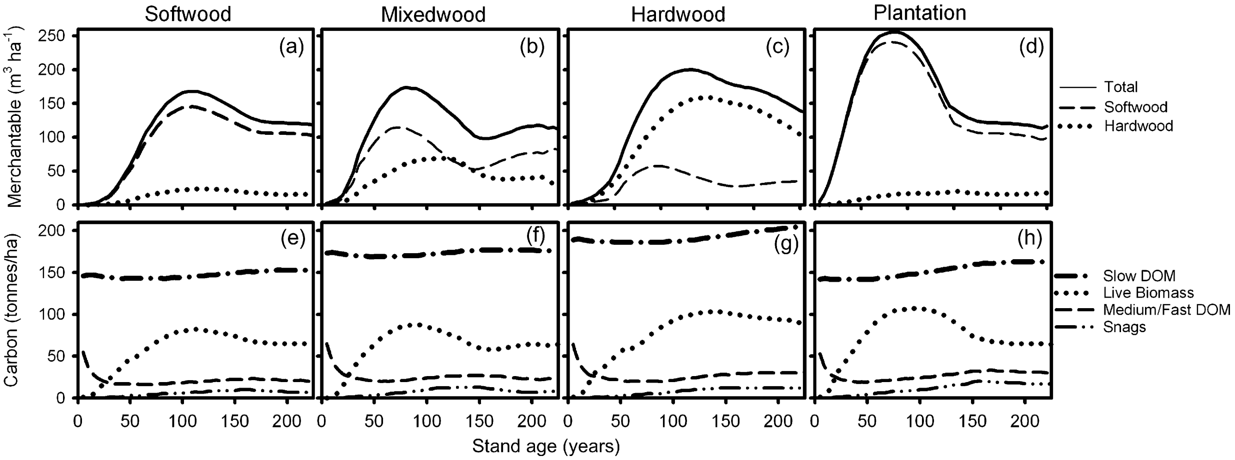

Fig. 2. Merchantable volume (a–d; projected with STAMAN) and carbon (e–h; projected with CBM-CFS3) stand yields for softwood, mixedwood, hardwood and softwood plantation types. Not all stand types are shown.

data on stand break-up, were assumed to follow SW development at ages ≥150 years. Volume growth response following selective harvest was estimated based on mean annual volume growth from age 50 to 100 years, as 2.5 $m^3\ ha^{-1}\ yr^{-1}$ for HW and 2 $m^3\ ha^{-1}\ yr^{-1}$ for SW and MW (Fig. 3a). Volume projections developed using STAMAN were used directly in the timber supply model, and were assumed to be static over time (e.g., no positive or negative tree growth or survival effect from climate change, insect disturbance, soil productivity from intensive management), as this was beyond the scope of this work.

2.2. Forest carbon pools

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al., 2002) was used to convert stand projections of HW and SW species merchantable $m^3\ ha^{-1}$ into C stored in living biomass (stem wood, foliage, stumps, branches, bark, coarse and fine roots) and DOM pools (litter, forest floor and soil detritus, standing snags and branches, coarse woody debris, and soil organic matter). In CBM-CFS3, live biomass is estimated using merchantable volume to aboveground biomass expansion parameters calibrated for the Atlantic Maritime region from the national forest inventory dataset (Boudewyn et al., 2007). Belowground living biomass stored in coarse and fine roots is estimated using regression equations based on SW and HW aboveground biomass (Kurz et al., 1996; Li et al., 2003). Transfers of live biomass to DOM pools depend on amount of SW and HW biomass present, biomass accumulation or decline over time, and biomass turnover rates (Kurz and Apps, 1999). Natural or human-caused disturbance can trigger stand type and age-structure conversions, resulting in C transfer from live biomass to DOM pools. Transfer of C from DOM to the atmosphere is controlled by DOM decay rates (Kurz and Apps, 1999). C stored in live biomass can also be released directly to the atmosphere from natural or human-caused disturbance such as insect outbreaks, wildfire, or harvesting.

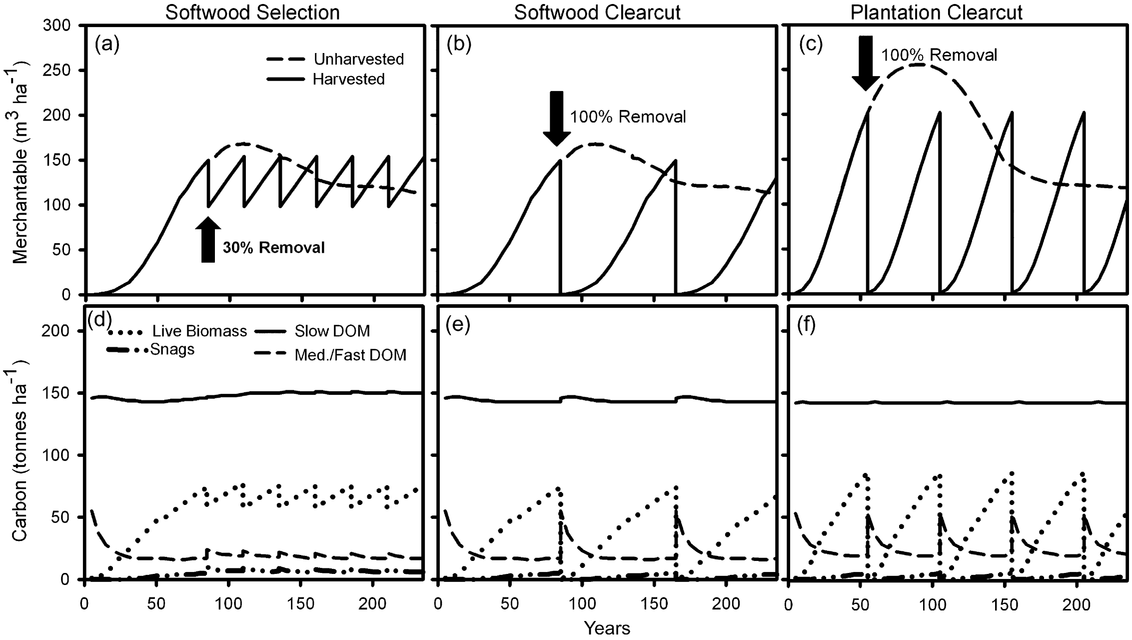

Fig. 3. Stand yields of total merchantable volume (a–c; projected with STAMAN) and carbon stored (d–f; projected with CBM-CFS3) in live biomass, snags (stem and branches), and dead organic matter (DOM) slow (humus and soil C) and medium to fast (litter, roots, etc.) pools for three example stand type and treatment combinations. Dashed lines (a–c) represent volume growth with no harvesting.

Stand-level C was grouped into four broad pools: (1) live biomass, (2) standing snags and branches, (3) very fast to moderate decay DOM (litter, forest floor coarse woody debris and soil detritus), and (4) slow to very slow decay DOM (humus and mineral soil organic matter). Stand dynamics for each of these four pools were represented as age-dependant C yields (Figs. 2e–h and 3d–f), allowing Woodstock model optimization of stand treatments to maximize C stored in the forest. Methods used here to represent stand live biomass and DOM dynamics in Woodstock are similar to those described by Neilson et al. (2007, submitted for publication).

Rates of live biomass accumulation, turnover, and historical disturbance regimes are used in CBM-CFS3 to initialize C stored in DOM pools prior to simulation. Soil C accumulation and decay rates are dependent on complex interactions between light, species, temperature, drainage, nutrient cycling, and historical disturbance regimes (Banfield et al., 2002; Peng et al., 2002), and are inherently uncertain when modeled with parameters calibrated for provincial and national scale forest C modeling in CBM-CFS3. Studies generally find reduced soil DOM as intensity of management increases (Fredeen et al., 2005; Jandl et al., 2007), especially when converting from old growth to second growth forests (Harmon and Marks, 2002). We simulated successive wildfire disturbance with a 100-year return interval and stand re-growth until slow DOM following disturbance was $\leq 1\%$ of levels at the time of the previous disturbance event. A 100-year fire return interval is considered short for the Acadian forest region (estimates vary between 200 and 1000 years by forest type and study – Lorimer, 1977; Wein and Moore, 1977; Loo and Ives, 2003; Wilson, 2005), however, other stand-replacing disturbances occur including spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks (35 year cycle; Royama, 1984; MacLean, 1980), wind events, and natural stand break-up (Taylor and MacLean, 2005). Although historic disturbances (e.g., fire versus insects) can differentially affect mineral soil DOM build-up and release over time, the slow to very slow DOM pools were not used directly in model simulations due to low confidence in absolute soil C pool estimates relative to small and uncertain changes of $\leq 5\%$ during stand development (Figs. 2e–h and 3d–f; IPCC, 2006; Jandl et al., 2007). In contrast to slow DOM pools, medium–fast DOM dynamics, largely depend on recent disturbances (<150 years), vary considerably more (Figs. 2e–h and 3d–f). Due to intensive fire suppression and aerial foliage protection for spruce budworm beginning in the 1950s, clearcut harvesting has recently become the most prevalent stand-replacing disturbance, so the final historical disturbance iteration before simulating future stand growth was modeled as clearcut harvest. Since live biomass growth rates are dependent on merchantable volume predictions, using high-yielding managed stand yields may overestimate historical live biomass and turnover to DOM pools. Therefore, DOM pools for planted, PCT, and post-selective harvest stands were assumed equal to unmanaged DOM levels until the stand transitioned to its managed state during initialization (Neilson et al., 2007).

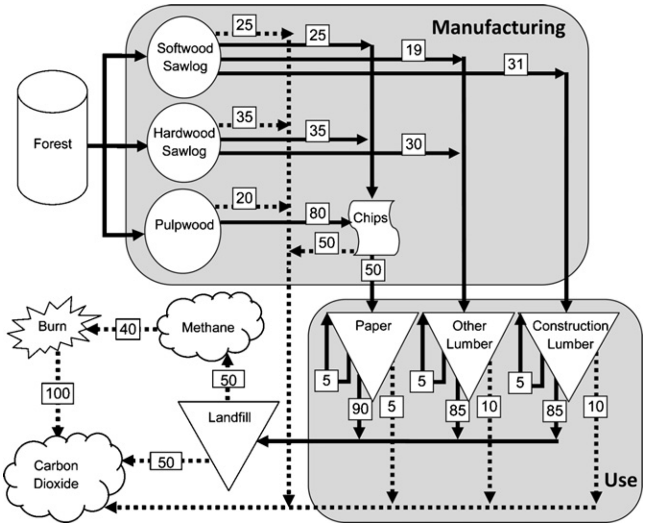

Fig. 4. Carbon transfer (%) from forest to product pools and release to the atmosphere via manufacturing and long-term use, adapted from the Canadian Budget Model of the Forest Product Sector (CBM-FPS; Apps et al., 1999), and used in CO_T. Carbon in harvest products (circles) delivered to mills is immediately transferred to wood products (triangle) or the atmosphere (burned residue, waste, etc.). Absolute release of carbon from product use and landfills to the atmosphere depends on age-based C retention rates (Fig. 5) and only %carbon transferred among destination pools are shown here.

2.3. Product carbon retention

C in merchantable log products was accounted independently of CBM-CFS3 through direct conversion of merchantable harvest volume to tonnes of C delivered to mills. Coefficients b for tonnes of merchantable C ha^{-1} by log product p (where 1 = SW sawlog, 2 = HW sawlog, and 3 = pulp log) for each stand were calculated as:

$$b^{p=1,2,3} = \sum_{s=1}^{S} v_{sp} g_s \cdot 0.5 \qquad (1)$$

where v is merchantable $m^3\,ha^{-1}$ multiplied by green wood specific gravity g (Panshin and Zeeuw, 1980) for species s to give kg of merchantable dry biomass ha^{-1}, and 0.5 is the amount of C per kg of dry biomass (IPCC, 2003).

An object-oriented model, referred to herein as CO_T (Carbon-Object Tracker), was developed to simulate product pool C transfer to alternative pool states through time; e.g., C in harvested roundwood, conversion to wood products, transfer to landfills, etc. CO_T was developed using Visual Basic.NET 2008 as a Windows application that interfaces with a Microsoft Access database used to store runtime options, pool properties such as age-dependant decay and transfer parameters, and simulation results. CO_T's object structure and capabilities were largely based upon C accounting methods and parameters used in the Carbon Budget Model of the Canadian Forest Product Sector (CBM-FPS; Apps et al., 1999). CO_T was designed solely to track the life-cycle of C objects through multiple transitions and states, and excludes CBM-FPS functions to track external energy use or energy substitution during harvest, transport, and manufacturing.

Mill roundwood utilization statistics, wood product retention curves, and landfill decay rates used in CBM-FPS (Kurz et al., 1992; Apps et al., 1999) were adapted for parameterization of CO_T (Fig. 4). Product retention curves define %C remaining over time in wood products (Fig. 2 in Apps et al., 1999). CBM-FPS tracks three harvest products – SW sawlogs, HW sawlogs, and pulpwood logs – into three wood product pools, namely construction lumber, other lumber (flooring, particle board, panels, etc.), and paper. C lost during mill processing or released from product aging is transferred immediately to the atmosphere (assumed to be burned for fuel or waste), recycled, and/or deposited in landfills (Fig. 4). In CBM-FPS, 80% degradable landfill material is assumed to decompose in equal proportions to CO_2 and CH_4 at a rate of $1\%\ yr^{-1}$, and the remainder at $\leq 0.001\%\ yr^{-1}$. Based on more recent Canadian forest product accounting work (NCASI, 2007), we reduced the landfill degradable proportion to 50% (proportions reviewed by Micales and Skog, 1997 range from 25 to 75%) and CH_4 captured and burned from landfill decay to 40% (Fig. 4); these rates are currently being updated in CBM-FPS (Werner Kurz, 2007, personal communication). See Micales and Skog (1997) for review of wood product decomposition processes and rates in landfills, and importance as a long-term C sink.

By tracking harvest products through manufacturing and wood product aging in CO_T, we calculated total future C storage in wood products and landfill pools from time of harvest (Fig. 5). One tonne of C for each harvest product was simulated in CO_T for 300 years, allowing C storage in paper, lumber, and landfill pools to be represented as separate harvest product yields (age-dependant state variable coefficients) in Woodstock (Fig. 5). Net C product storage was calculated as the difference between C retained in product and landfill pools minus the greenhouse gas (GHG) equivalent of methane (GHG warming potential of 23; IPCC, 2001) released to the atmosphere from landfill decay (Fig. 5). Since landfill decay is constant at 1% yr^{-1}, methane emissions begin to decline after 100 years as degradable landfill material becomes exhausted (i.e., less difference between net and gross storage; Fig. 5).

2.4. Model design

Woodstock uses a model II (Johnson and Scheurman, 1977) linear programming (LP) design to account and optimize forest area use choices over time. Harvest area is accounted through decision variables where x_{dijt} is the area of development (stand) type d (SW, MW, HW, plantation, SW PCT, MW PCT, and select cut SW, MW, and HW) harvested in period i and regenerated in period j with treatment choice t. Simulations used a 300-year planning horizon, with presented results limited to ≤250 years. Volume harvested or C stored per unit area was calculated using age-dependant yield coefficients. Eq. (2) was used to maximize harvest volume for sixty 5-year periods:

$$\text{Max}\quad \text{Volume Harvest} = \sum_{d=1}^{D=9}\sum_{i=-M}^{I=60}\sum_{j=1}^{J=60}\sum_{t=1}^{T=2} v_{dijt}x_{dijt} - \sum_{d=1}^{D=9}\sum_{i=-M}^{I=60}\sum_{j=1}^{J=60}\sum_{t=1}^{T=5} x_{dijt} \qquad (2)$$

where v is $m^3\ ha^{-1}$ harvested, M represents the oldest age class in period zero, and the second term minimizes area treated. Total forest C inventory stored was maximized as:

$$\text{Max}\quad \text{Forest C} = \sum_{d=1}^{D=9}\sum_{i=-M}^{I=60}\sum_{p=1}^{P=60} c_{d(i-p)}y_{dip} - \sum_{d=1}^{D=9}\sum_{i=-M}^{I=60}\sum_{j=1}^{J=60}\sum_{t=1}^{T=5} x_{dijt} \qquad (3)$$

where y_{dip} is area by development type and age $(i-p)$ for period p, and c is t ha^{-1} of C stored in live biomass, snags, and fast–medium DOM pools. Constraints were used to limit between-period fluctuations of total harvest to ≤10%, and harvest products to ≤5%.

In order to store and age harvest products, additional variables were needed to account for C transfer and storage from forest to products over the planning horizon. Four extra 'development types' were added to the model to represent pools of C, with the first as a source pool ($y_{s=0}$ representing the atmosphere), and the remaining three as product sinks for SW sawlog, HW sawlog, and pulpwood log pools ($y_{s=1,2,3}$). For these C pool state variables (y_s), units typically thought of as area of stand type d, are now considered as units of C in product pool s, allowing C increases in product sink pools to be inventoried, aged over time, and linked to age-dependant %C retention coefficients in CO_T. Increases to each product sink ($y_{s=1,2,3}$) were controlled by constraining units of $y_{s=0}$ to be reduced and $y_{s=1,2,3}$ increased in equal abundance to units of C contained in respective products harvested in period j. To accommodate these methods in Woodstock, three 'treatments' were added to the model, each representing a different mill manufacturing process (SW sawlog, HW sawlog, and pulpwood), and constrained to control transfer of C units (where C units are equivalent to units of 'area' in Woodstock) from source to sink pools (represented as theme states in Woodstock) by harvest product amount produced.

The only purpose of the source pool variable was to satisfy ending inventory constraints that require $\sum y^s$ balance within and between periods (i.e., increasing units of $y_{s=1,2,3}$ must accompany an equal reduction of $y_{s=0}$). Therefore, the initial source pool value must be ≥total possible product C harvest to avoid inadvertently constraining harvest level through inventory constraints. Initial units in source and sink pools were set at 100 million and zero, respectively.

Total wood product inventory was maximized as:

$$\text{Max}\quad \text{Product C} = \sum_{s\notin 0}^{S=3}\sum_{i=-M}^{I=60}\sum_{p=1}^{P=60} r_{s(i-p)}y_{sip} - \sum_{d=1}^{D=9}\sum_{i=-M}^{I=60}\sum_{j=1}^{J=60}\sum_{t=1}^{T=5} x_{dijt} \qquad (4)$$

where r is total %C retained in paper, lumber, and landfill (Fig. 5; C retained) for each harvest product C unit stored as $y_{(s\neq 0)ip}$. Total forest and wood product carbon inventory was maximized by summing Eqs. (3) and (4). Additional simulations tested for differences when discounting future value of harvest or C stored at 4%, applied to all objective function coefficients.

Influence of avoided fossil-fuel emissions from substitution of lumber over more fossil-fuel demanding steel or concrete house frame designs on forest management was explored separately from main scenarios above. We identified substitution rates (t C emissions avoided per m^3 of lumber used) from other studies and adapted units to allow total C storage plus avoided C emissions (substitution rate X softwood construction lumber production) to be maximized. Estimates of avoided emissions from substitution

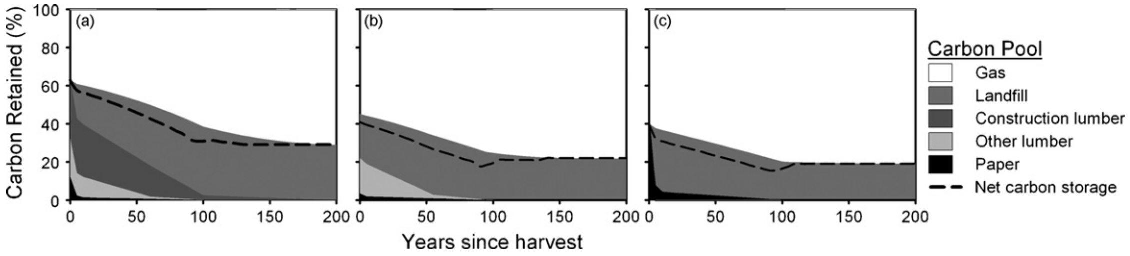

Fig. 5. Percent carbon retained in primary use products (construction/other lumber, paper) and landfill pools over time for (a) softwood sawlog, (b) hardwood sawlog, and (c) pulpwood harvested. Calibration was adapted from the Canadian Carbon Budget Model of the Forest Product Sector (Apps et al., 1999) and NCASI (2007), and modeled using CO_T. Net carbon storage (dashed line) equals carbon retained in products and landfills minus the GHG impact of CH_4 released from landfill decay. Only 200 years are shown, as future carbon release rates remain relatively constant.

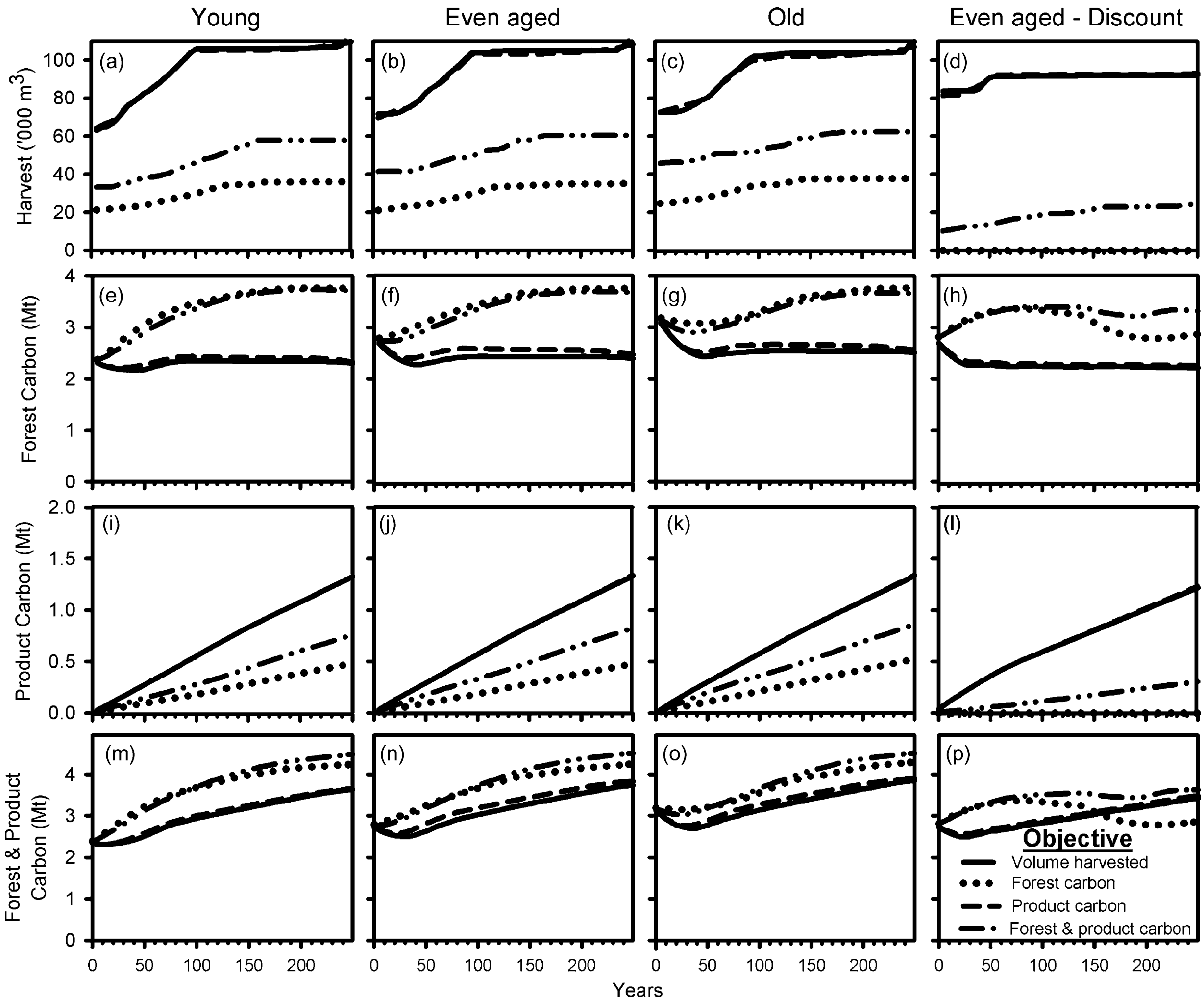

Fig. 6. Volume harvested (a–d), and carbon stored in forest (e–h), product (i–l) and forest and product (m–p) pools over 250 years for four alternative objective functions (see legend) and three initial forest age class structures (young, even-aged, old). A 4% discount factor was applied to objective function coefficients for the even-aged initial age-structure for results in d, h, l, and p.

vary from 0.5 to 0.9 t C m^{-3} for steel (Perez-Garcia et al., 2005a) and 0.1–0.3 t C m^{-3} for concrete (Petersen and Solberg, 2003; Perez-Garcia et al., 2005b; Lippke and Edmonds, 2006), depending on life-cycle assumptions (e.g., construction materials, building codes, geographic location), completeness and time period of assessment ('gate to gate' versus 'cradle to grave'), and whether sequestration in forest and product pools is considered in addition to embodied (raw material extraction to disposal) emissions (Upton et al., 2008). Since rates of substitution found in the literature are variable and, in general difficult to estimate and apply to alternate scenarios, we modeled a broad array of substitution rates of 0.125, 0.25, 0.5, and 1 t C m^{-3} to ascertain the range of influence substitution accounting could have on management when maximizing total C storage, and also to demonstrate an alternate use of this modeling framework for incorporating other C emissions.

We conducted several sensitivity analyses to quantify effects on results of changing plantation productivity, DOM and landfill decay parameters, product use, exclusion of treatment types, and planning horizon when maximizing total C storage for the even forest age-structure. Model sensitivity, measured as % change in mean harvest rate, area by treatment, and C sequestered in forest and product pools for years 1–200, was evaluated as a function of selected parameter changes (−50% to +300%) for a total of 17 scenarios.

3. Results

3.1. Initial age class structure effects on C

Initial forest age class structure (young, even-aged, old; Fig. 1) had only minor effects on long-term forest management design, though it did affect initial harvest levels and cumulative C storage in product pools (Fig. 6). Initial volume harvested when maximizing total C (forest and product storage) was 28% lower for a young than old forest, but only 12% lower at the end of 100 years. In contrast, when maximizing harvest, volume harvested after 30 years differed <1% between initially young and old forests (Fig. 6a–c). When maximizing total C storage, product C storage was 10% less for initially young than old forest at the end of 200 years, but when maximizing harvest there was no difference (Fig. 6i–k).

When total C was maximized, only the old initial age-structure resulted in a net source of C (mean −0.14 t ha^{-1} yr^{-1} for years 1–50), caused by higher rates of harvest in mature–old (>100 years) stands to (1) capture large declining pools of C stored in live

Table 1
Summary of mean tonnes of C sequestered $ha^{-1}\,yr^{-1}$ by forest, product, and total pools, and mean harvest for years 1–200, for five alternative management objectives for the even-aged test forest (Fig. 1).

Objective	Mean tonnes of C $ha^{-1}\,yr^{-1}$ by pool				Mean harvest ($m^3\,ha^{-1}\,yr^{-1}$)
Maximized	Forest	Product	Total[a]	Total + S[b]	
m^3 harvest	−0.055	0.181	0.126	0.260	3.16
Product C	−0.035	0.183	0.148	0.287	3.13
Forest C	0.164	0.064	0.228	0.277	0.98
Total[a]	0.155	0.110	0.265	0.351	1.71
Total + S[b]	0.114	0.138	0.252	0.361	2.15

[a] Total = forest C + product C.

[b] Substitution benefit factor; displaced fossil-fuel emissions set equal to 0.25 t C m^{-3} of lumber produced.

biomass into product storage and (2) promote stand C sequestration rates through regeneration. Without any harvest, stand C sequestration averaged 0.57, 0.34, and 0.11 t $ha^{-1}\,yr^{-1}$ for the first 50 years, for young, even-aged, and old age-structures, respectively. When total C was maximized, higher sequestration rates for younger stands resulted in 28 and 9% less initial harvest in young and even-aged, respectively, compared to old forest (Fig. 6a–c).

3.2. Effects of objective functions and management strategies

Similar forest management strategies resulted when the objectives were to maximize harvest (Eq. (2)) or C stored in product pools (Eq. (4)), each causing a dramatic shift from existing stand types to managed SW plantations, and harvest increases for the even forest age-structure from current levels of 72,000 to 103,000 $m^3\,yr^{-1}$ by year 100 and 105,000 $m^3\,yr^{-1}$ by year 200 (Fig. 6a–c). In contrast, maximizing forest C reduced initial harvest from 72,000 to 21,000 $m^3\,yr^{-1}$ (Fig. 6a–c), and future harvest increased to only 30,000 $m^3\,yr^{-1}$ and 38,000 $m^3\,yr^{-1}$ at the end of 100 and 200 years, respectively.

Maximizing forest C, compared to maximizing product C or harvest, increased mean rotation length from 60 to 155 years, allowing trees to continue to sequester and store C in live biomass pools. Forest live biomass was highly correlated ($r = 0.97$) with timber volume, and since live biomass C increase during stand growth of 100 t ha^{-1} exceeded the DOM and snag pool storage of 25 t ha^{-1} (Figs. 2 and 3), in general, strategies that increased cumulative growing stock during the planning horizon optimized forest C. After 200 years of simulated forest management to maximize forest C storage for the 30,000 ha test forests, forest C increased from 2.33 to 3.75 Mt for the initially young, from 2.76 to 3.72 Mt for the even-aged, and from 3.19 to 3.76 Mt for the initially old forest (Fig. 6e–g). In comparison, when volume harvested or product C storage was maximized, forest C at year 200 was 2.4 Mt.

When C in forest and product pools was maximized together (total storage; Eq. (3) plus (4)), harvest increased by 173% (Fig. 6a–c), compared to maximizing only forest C, mean clearcut rotation age declined from 155 to 120 years (for HW, from 275 to 235 years, SW 160–135 years, MW 145–135 years, and SW plantations 125–100 years). Despite increased harvest levels and treatment schedule changes, maximizing total C reduced forest C by <2%, compared to maximizing forest C. Carbon storage benefits of harvesting stands earlier must, therefore, greatly outweigh the marginal benefits of preserving on-site C in declining stands (>100–120 years old; Fig. 2), when transfer of C from forest to product storage is considered. Harvested wood products in use and landfills accounted for 3% and 12%, respectively, of total C storage at 200 years when maximizing total C; and doubled in proportion when maximizing harvest. Percentage of lumber, paper, and landfill storage in the product pool was relatively constant across objectives at 39%, 3%, and 68%, respectively, at 100 years, and 18%, 2%, and 80%, respectively, at 200 years. At 200 years, there was less difference in total C storage among objectives (1 Mt; Fig. 6m–o), compared to when considering only forest C storage (2 Mt; Fig. 6e–g). Table 1 presents mean sequestration and harvest for years 1–200 by objective.

Mean area clearcut increased by 40% during the first 100 years when maximizing all C pools compared to only forest C (Fig. 7c–d), while planting and PCT levels remained similar. Area allocated to selection harvest treatments increased from 7500 to 13,200 ha in HW and from 0 to 2500 ha in MW at 200 years when maximizing total C compared to only forest C (Fig. 7d). For all simulated scenarios, conversion of natural SW to more productive SW PCT and/or plantations was favored over selection harvest of SW. Plantation area increased from 0 to 20,000 ha (two thirds of the test forest) over 200 simulated years when product C or harvest was maximized, versus to only 5000 ha when forest or total C was maximized. In contrast, when maximizing forest C compared to only products, PCT area increased from 2500 to 13,500 ha over 200 simulated years. Despite seemingly large differences among optimal planting and PCT treatment strategies for alternative objectives, constraining area of PCT or planted stands to zero in all planning periods caused no change in total C stored for years 1–100, and <2% reduction after 100 years when total C was maximized; mean forest plus product sequestration rate for years 1–200 declined by 6–7% (Table 2). On the other hand, when maximizing total C, constraining area of MW and HW selection harvest treatments to zero (SW selection harvest area was nil) reduced total C storage by 8.5% at 200 years and reduced mean forest plus product C sequestration rate by 23% (Table 2). Constraining clearcut harvest to zero caused mean forest plus product C sequestration rate to decline by 65 and 37% (Table 2), due to inability to regenerate declining stands (i.e., those having negative sequestration rates) that were generally inoperable for selection harvest.

3.3. Effects of discounting and product substitution

Discounting objective function coefficients by 4%, to increase the weight of C stored or volume harvested earlier in the planning

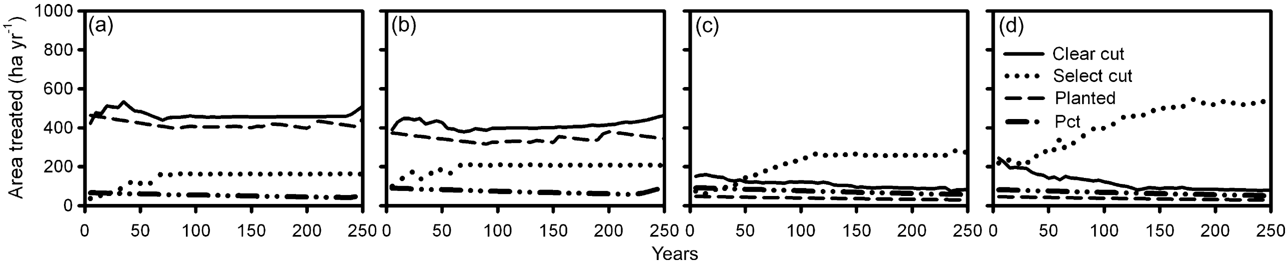

Fig. 7. Area treated (ha yr^{-1}) by treatment over 250 years for an even initial age-structure and four alternative objective functions, to maximize: (a) volume harvested, (b) wood product C storage, (c) forest C storage, and (d) C storage in the forest and products.

Table 2

Model sensitivity, measured as % change in mean harvest rate, area by treatment, and C sequestered in forest and product pools for years 1–200, as a function of selected parameter changes (−50% to +300%)

Parameter	Change[a]	%Change of mean rates for years 1–200							
		Harvest ($m^3\ yr^{-1}$)	Area treated ($ha\ yr^{-1}$)				Sequestration ($t\ C\ yr^{-1}$)		
			Clearcut	Select	Plant	PCT	Forest	Product	Total
Maximize total C[b]	No change	51,200	129	397	38	69	4650	3300	7950
Management									
Plantation yield	+25%	18	47	−36	389	−100	14	18	16
	+50%	35	69	−51	476	−100	56	35	47
PCT and plantation fast–medium DOM	−25%	3	−18	25	−33	−22	−13	4	−6
	−50%	5	−29	42	−71	−44	−21	7	−9
Clearcut treatment	Exclude	−41	−100	24	−100	−100	−65	−37	−53
Plant treatment	Exclude	−2	−16	19	−100	−9	−10	−1	−6
PCT treatment	Exclude	12	−11	29	133	−100	−21	13	−7
Select treatment	Exclude	−43	30	−100	89	35	−7	−46	−23
Product use									
Log lumber recovery (softwood = 45%, hardwood = 30%)	+25% (56, 38%)	−3	−2	−2	−3	−3	1	7	4
	+50% (68, 45%)	−3	−3	−1	−3	−3	1	16	7
Lumber in use[c] (100 years)	+100% (200 years)	−3	−2	−2	−3	−3	1	7	4
Lumber production	Exclude[d]	−3	−2	−2	−3	−2	2	−28	−10
Landfill decay									
Decay rate (1% yr^{-1})	+300% (4% yr^{-1})	−3	−2	−2	−3	−3	1	−21	−8
Landfill material non-degradable (50%)	+50% (75%)	8	9	4	9	9	−6	42	14
	−50% (25%)	−9	−4	−8	2	−2	4	−38	−13
Methane captured (40% of released)	0% (0%)	−2	−2	−2	0	−2	1	−12	−4
	+100% (80%)	3	2	3	1	2	−2	14	5

The scenario analyzed maximized total C for the 30,000 ha even-aged test forest. The first row shows absolute rates for the base run with no parameter changes.

[a] Values represent % change to parameter values; where possible, resulting values are given in parentheses.

[b] Base run absolute values are shown in this row, all other values in rows below show % change from these values; e.g., 129 ha clearcut in the base run minus 100% equates to 0 ha treated.

[c] 100 years until <5% of construction and other lumber (panels, flooring, etc.) products remain in use (homes, buildings, etc.). Here we doubled lumber retention time in use.

[d] Only paper produced only from logs harvested.

horizon, resulted in large differences in management strategies among alternative objectives. With discounting applied, there were negligible differences in management strategies among the three initial age-structures, and therefore results are presented only for the even-aged initial age class structure (Fig. 6d, h, l, p). No harvest occurred when discounted forest C was maximized (Fig. 6l), since the contribution of current standing biomass when discounted out-weighed benefits of increased sequestration in regenerating stand conditions and product pools. Maximizing discounted total C (Fig. 6d) reduced mean harvest for years 1–200 by 67%, compared to maximizing total C (Fig. 6b). Long-term harvest levels were reduced by 13% in favor of a 15% increase in current harvest when discounted product C or volume harvested was maximized (Fig. 6d). Interestingly, long-term total C storage remained stable or increased under an objective to maximize discounted total C, whereas it decreased by 19% from year 90 to year 200 under an objective to maximize discounted forest C (Fig. 6p).

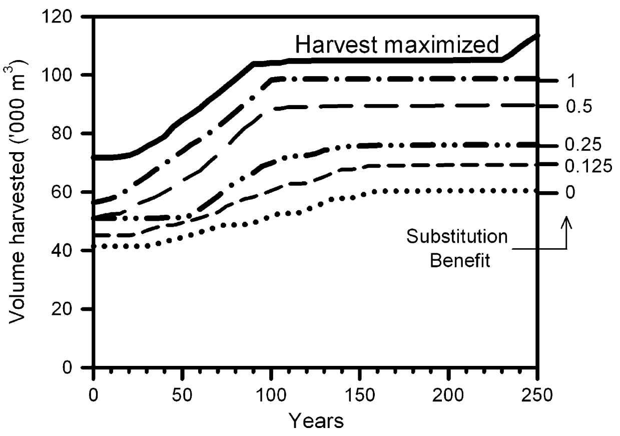

Fig. 8. Volume harvested over 250 years for the even initial age-structure when harvest is maximized (solid line; same as Fig. 6b), versus maximized forest and product C storage (broken lines) under five lumber substitution benefit levels ranging from 0 to 1 t C abated from the atmosphere per m^3 of lumber used relative to more fossil-fuel demanding products such as steel or concrete. The zero benefit line is equivalent to values in Fig. 6b when forest and product C storage is maximized.

When avoided emissions from product substitution were accounted for, in addition to total C storage, the emphasis on intensive forest management (shorter rotations, more planting and harvest) increased with substitution benefit, measured as t C offset per m^3 of lumber used in place of other more fossil-fuel demanding alternatives (Fig. 8). Mean harvest for years 1–200 increased by 14, 26, 46, and 67% for substitution factors of 0.125, 0.25, 0.5, and 1 t C m^{-3}, in comparison to harvest that maximized total C (Fig. 8; no substitution).

3.4. Model sensitivity

Since C in landfills persists for >100 years and objectives consider cumulative C pool dynamics over the 300-year planning horizon, harvest levels when maximizing total C were extremely sensitive to planning horizon lengths <120 years. Mean harvest varied from 10,000 to 200,000 $m^3\,yr^{-1}$ for planning horizon lengths of 40–120 years when total C was maximized. Similar effects of planning horizon length on optimal strategies to maximize C storage were also shown by Schlamadinger and Marland (1995), Perez-Garcia et al. (2005a), and Upton et al. (2008). Mean harvest for years 1–200 was within 10% of maximum harvest when total C plus avoided emissions (using 0.25 t C m^3) was maximized and the planning horizon was 750 years; further planning horizon increases were limited by computer resources. Harvest level was insensitive when discounted total C and avoided emission were maximized for planning horizons >120 years. With planning horizons >80 years, harvest levels were similar whether harvest or C stored in products was maximized.

Table 2 presents sensitivity of mean harvest, sequestration, and treatment area over years 1–200 for changes in plantation yield, DOM storage, product retention, decay parameters, landfill decay, and CH_4 release for the even initial forest age-structure. Increasing plantation yield by 25 or 50% caused the greatest change in treatment schedule, harvest, and C sequestration rates. No PCT occurred when plantation yield was increased >10%. Forest C sequestration increased more (57%) than product storage and harvest (35%) when plantation yield was 50% higher (375 $m^3\,ha^{-1}$ at peak yield). While a 50% higher plantation yield seems unlikely for sites with unmanaged SW peak yield of 150 $m^3\,ha^{-1}$ (Fig. 2a), this yield has been recorded in New Brunswick (Pelletier and Pitt, 2008). Analyses that reduced DOM pool storage by 25 and 50% in planted and PCT types increased mean harvest for years 1–200 by only 3–5%, and reduced mean total C storage <2%. When plantation and PCT DOM storage was reduced by 25%, area of these treatments declined by 22–33%, in favor of 25% more selection harvest.

Increasing lumber extracted from sawlogs by 25% or 50%, increasing lumber retention time in use by 100%, or excluding lumber production (100% of raw material chipped for paper), caused only −1–3% difference in forest C sequestration rate, harvest, and area treated, but did result in larger (7 to −28%) changes in mean rate of C sequestered in product pools (Table 2).

Product pool storage was more sensitive to landfill decay and CH_4 release than to lumber manufacturing and retention in use parameters. Increasing landfill decay from 1% to 4% reduced mean harvest and total C sequestration rate for years 1–200 by 3% and 8%, respectively. Increasing the non-degradable landfill proportion by 50% (Table 2), resulted in 8% and 40% more harvest and C sequestered in product pools, respectively, with similar but opposite effects when reduced by 50%. Doubling rate of capture of CH_4 from landfill decay (from 40% to 80%, which is expected as methane capture systems become more prevalent over time; NCASI, 2007) increased product and total pool C sequestration rate by 14% and 5%, but caused little change in harvest or areas of treatments (±3%).

The sensitivity analyses in Table 2 indicated that optimum treatment choices to maximize total C storage were highly dependent on biomass productivity, DOM retention, and proportion of degradable landfill material. Harvest and sequestration rates were generally more sensitive to management objective (maximize forest versus product C; Table 1), discounting (Fig. 6), and planning horizon changes than to product use and landfill parameter changes (Table 2).

4. Discussion

4.1. Forest management effects on carbon storage

This paper demonstrates, to our knowledge, the first model II LP formulation able to maximize C storage in live biomass, DOM, forest products, and abated fossil-fuel GHG emissions from product substitution. Maximizing harvest, product C, forest C, and total C resulted in mean C sequestration over 200 simulated years in forest and product pools of 0.13, 0.15, 0.23, and 0.26 t C $ha^{-1}\,yr^{-1}$, respectively (Table 1). For the 30,000 ha test forest over a 200-year horizon, this would equate to 3.52, 3.65, 4.13, and 4.35 Mt C, respectively. Product C sequestration for 200 simulated years when maximizing product C approached rates of forest sequestration when forest C was maximized, 0.178 t $ha^{-1}\,yr^{-1}$ versus 0.219 t $ha^{-1}\,yr^{-1}$, respectively (Table 1), where forest sequestration was calculated as the difference between rates when maximizing product versus forest C. This marginal difference between maximum sequestration rates in the forest and product pools clearly indicates the importance of product pool accounting. It also indicates the reason that relatively little difference in total C storage occurred between alterative objectives, compared to accounting for forest C storage alone; at year 200, 54% more forest C was stored when maximizing forest C compared to maximizing harvest level, however, total forest plus products C was 23% higher when maximizing forest C compared to harvest, and only 13% more when substitution benefit was added (assuming 0.25 t C abated per m^3 of softwood lumber).

Schlamadinger and Marland (1995) demonstrated that net C balance at the end of 100 years, using a hypothetical forest simulation model, was similar whether trees are harvested and used for energy and products or the forest was protected from harvest. Perez-Garcia et al. (2005a) modeled effects of rotation length for stands in the Pacific Northwest United States on forest and product C storage, and demonstrated that when avoided emissions from substitution benefits were included, shorter rotations increase total C storage. The relatively small difference in C storage between alternative management designs (no harvest versus intensive harvest) shown here and in Perez-Garcia et al. (2005a) and Schlamadinger and Marland (1995), when accounting for product C and avoided emissions versus only forest C, has important implications. Planning to maximize total forest plus products C storage permitted near doubling (173%) of harvest, promoted more intensive forest management, and increased total C storage by 5% and sequestration rate by 16%, compared to maximizing forest C alone. However, the above 5% increase in total storage and effect on harvest may be counterbalanced by forest-sector raw material extraction, manufacturing, and transportation emissions. Apps et al. (1999) show Canadian forest product stocks grew by 25 Mt C yr^{-1} in 1989, but only by <11 Mt C yr^{-1} if sector emissions were accounted. These sector emissions, however, are more than offset when avoided embodied emissions from wood substitution are calculated (Apps et al., 1999).

Maximizing avoided emissions from substitution, in addition to total C, increased mean harvest for years 1–200 to within 46, 38%, and 31% of maximum possible harvest for substitution rates of zero (no substitution), 0.125, and 0.25 t C m^{-3}, respectively. Avoided emissions from substitution ranged from 0 to 1 t C m^{-3} for studies cited (Petersen and Solberg, 2003; Perez-Garcia et al., 2005a,b; Lippke and Edmonds, 2006; Upton et al., 2008); with most between 0.1 and 0.3 t C m^{-3}. NCASI (2007) estimated avoided emissions from substitution for the Canadian forest product sector to be significantly lower (0.011 t C m^{-3}) than the above studies, but may be conservative as housing sector avoided emissions (1) were calculated as a function of all sawnwood and panels produced in Canada, compared to only product used for house construction, as in other studies; and (2) include forest and product use and landfill stock changes in addition to embodied emissions for alternative house frame designs. Including only embodied emissions, to avoid double counting forest and product pool changes modeled here, would increase the NCASI substitution rate by 28% (interpreted from Upton et al., 2008; NCASI, 2007).

Trade-offs between storage of C in products versus conversion to biofuel to reduce fossil-fuel and landfill methane emissions were not explored in this study. However, net C emissions would be reduced if biomass is first used for construction and then burnt for fuel after building disposal (Eriksson et al., 2007). Similarly, Petersen and Solberg (2003) calculated avoided emissions of 1.23 t C m^{-3} for use of hardwood in place of tile flooring, if used for biofuel after building demolition. Further evaluation of effects of biofuel strategies on C dynamics is possible by adapting the modeling framework to include bio-energy treatments and state variables to account for additional avoided emissions. Benefits of wood use in simulations increase cumulatively over time, since temporary storage in forests is ecologically constrained by site productivity, species, and natural disturbance, while C sequestration in landfills (semi-permanent storage of non-degradable material) and avoided emissions through product substitution or biofuels is cumulative. However, such increases, calculated many centuries in the future, are clearly uncertain and also reduced when discounted to present value.

Climate change and natural disturbance impacts on forest dynamics were beyond the scope of this study and were not simulated. Severe insect outbreaks or forest fire will reduce projected forest C storage potential, with reductions due to insect outbreaks possibly exacerbated further by climate change (e.g., mountain pine beetle, *Dendroctonus ponderosae* Hopkins; Kurz et al., 2008a). Although projected increases in atmospheric CO_2 and N deposition may increase forest productivity, negative impacts of increased natural disturbance are predicted to overwhelm benefits as climate change continues (Kurz et al., 2007, 2008a,b). If mature stands are, in general, more vulnerable to natural disturbance, then increased harvest may reduce risk to natural disturbance (Routledge, 1980), increase product C storage and avoided emissions, and may partially compensate for tree mortality and resulting forest C losses from natural disturbance. Thus, both climate change and natural disturbance effects should increase GHG benefits of product use and avoided emissions, relative to forest C storage, in analyses.

4.2. Which treatments optimize C storage?

Due to higher wood density, HW stored 15% more C ha^{-1} at peak yield than MW and SW stands (103, 87, and 82 t ha^{-1} of C in live biomass, respectively), generally similar to levels (75–95 t ha^{-1}) modeled and reviewed by Neilson et al. (2007). In contrast to Neilson et al. (2007), we simulated ingrowth of trees during stand projections, allowing long-term C storage to persist. This was especially true for uneven-aged stand types dominated by sugar maple and yellow birch (200–400 year lifespan), which had relatively stable ingrowth and continued C storage. The stability of stand live biomass and higher C storage in HW stands lengthened mean clearcut rotation age from 90 to 275 years (essentially a no clearcut policy) when maximizing forest C compared to maximizing harvest, and to 235 years when maximizing forest and product C. This was about 100 years longer than rotations in SW and MW types.

While planted and PCT stand types had 35% more peak volume than non-intensively managed types, peak C yield difference for combined live biomass and DOM pools was also 25% higher for PCT, planted, and HW types than for SW and MW. Therefore, conversion of HW stands to managed SW and MW types yields virtually no forest C benefit. Total C storage was generally insensitive to constraints placed upon amounts of SW planting, PCT, or SW selective cut treatments, but was reduced by 8.5% when HW and MW selective cut treatments were omitted. Selective cut regimes in HW and MW stands reduced conversion to naturally regenerating SW and MW, maintained on-site forest C storage, enhanced sequestration rates in older stands, and allowed transfer of C to product storage following each harvest entry. While effects of selective cut treatments on stand C cycling were modeled here empirically using CBM-CFS3, other studies using process models and field measurements corroborate benefits of partial stand removal for conservation of DOM C and wood production (Thornley and Cannell, 2000; Harmon and Marks, 2002; Garcia-Gonzalo et al., 2007; Jandl et al., 2007).

4.3. Application of the framework

Solve time for our hypothetical 30,000 ha forest model was 20 s with 4000 decision variables and 20,000 constraints, using a high-end PC with 4GB of RAM. Since coefficients used to quantify C stored in live biomass and DOM for each stand type did not directly increase constraints or variables, model solve times remained relatively unchanged from the base model with no C accounting coefficients. Additional variables and constraints required for product pool accounting also had little effect on solve times, as accounting was aggregated at the forest level, rather than tracking product storage by stand. We successfully used this design, without incurring significant increases in solve time, in two real-world, complicated industrial timber supply models for forests in New Brunswick: (1) the J.D. Irving, Limited Black Brook District (200,000 ha) model with hundreds of thousands of decision variables and constraints, and (2) the AbitibiBowater Inc. Upsalquitch Crown License model (410,000 ha; Neilson et al., submitted for publication). Solve times were greatly improved by enumerating all life-cycle product pool dynamics using CO_T into simplified yield coefficients of C storage per unit log harvested over time.

Remsoft Inc. has developed a user tutorial to demonstrate the application of our model within the Remsoft Spatial Planning System. To date, the tutorial has been presented by Remsoft in Canada, New Zealand, and the United States (Andrew Cogswell, Remsoft Inc., personal communication, 2008). Alternatively, integration of product C life-cycle yields into other forest simulation or optimization programs is also feasible. CO_T remains as a research application and is presently not supported, however, simple flows of C though alternative material states as modeled here and in the CBM-FPS can be replicated using commercial object-flow models such as STELLA (Isee Systems, 2008).

5. Conclusions

We have presented a novel approach to simultaneously maximize C sequestered in live biomass, DOM, forest products, and abated emissions from product substitution, through optimized forest treatment scheduling using a model II LP formulation. Harvested wood products in use and landfills accounted for 6% and 24%, respectively, of total C storage over 200 simulated years, when the objective was to maximize harvest levels. Amount of product C, especially in landfills, exceeded that generated by excluding trees from harvest to maintain on-site forest C, as shown when maximizing total C compared to forest C. An objective to maximize harvest resulted in an average harvest over the 200-year simulation of 3.16 m^3 ha^{-1} yr^{-1} and total C sequestration of 0.13 t ha^{-1} yr^{-1}, versus 0.98 m^3 ha^{-1} yr^{-1} and 0.23 t ha^{-1} yr^{-1}, respectively, for an objective to maximize forest C. When the objective was to maximize total C storage in product and forest pools, harvest level and total C storage were 173% and 5% higher, respectively, compared to those with an objective to maximize forest C; and 218% and 6% higher, respectively, when the objective was to maximize substitution benefits and total C storage.

Optimum treatment schedules to maximize C storage were dependent on pools accounted, stand live biomass growth rates, soil DOM dynamics, planning horizon length, discount rate, and treatment constraints. This complexity necessitates integrated forest planning models, as presented here, and improved information on DOM and product pool dynamics. Our results reinforce the need to account for all forest-sector C debits and credits in developing sound policies to maximize forest reductions of GHG. Linear optimization methods described here for C accounting using Woodstock (a forest optimization program used throughout the world) permit use of our approach for other areas and industrial forest management problem sizes.

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