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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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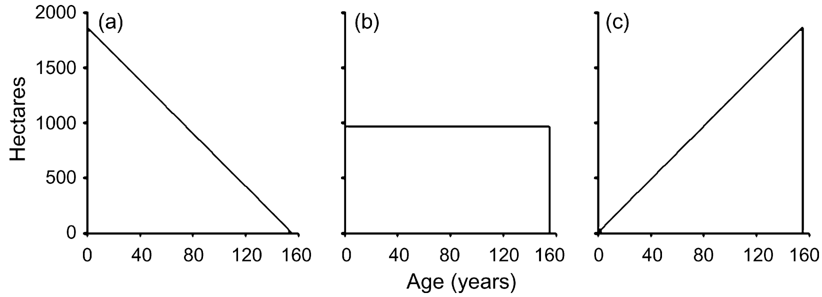

Fig. 1. Three initial age-structures for a 30,000 ha hypothetical test landbase were simulated: young (a), even-aged (b), and old (c). Area per 5-year age class is shown.

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 $\leq$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 $\geq$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 $\geq$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