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Spatial distribution of carbon in natural and managed stands in an industrial forest in New Brunswick, Canada

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Abstract

Industrial forest could be managed to enhance carbon (C) sequestration together with other ecological and socio-economic objectives. However, this requires quantifying C dynamics of all major forest types within the management area, over the whole forest rotation. We used data from permanent sample plots and temporary forest development survey plots to generate volume yield curves and used the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to estimate C yield and dynamics over a rotation for major forest types in northern New Brunswick, Canada. We compared C yields of natural versus managed and hardwood versus softwood forest under different silviculture treatments over the entire rotation. Carbon in 40–80-year-old and > 80-year-old tolerant hardwood stands averaged about 115 and 130–142 t ha^{-1}, respectively, while softwood spruce (*Picea* sp.)–balsam fir (*Abies balsamea* (L.) Mill.) 40–80 and > 80 years old averaged 90 and 88–94 t C ha^{-1}. Among 10 stand types, total C ranged from 50 to 109 t ha^{-1} at age 50 years, 92–138 t ha^{-1} at age 100, and 79–145 t ha^{-1}at age 150 years. C in most stand types declined from age 100 to 150 years, except for eastern white cedar (*Thuja occidentalis* L.), sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britton). At age 100 years, planted softwood stands had 94–135 t ha^{-1}, versus 92–117 t ha^{-1} for natural softwoods and 127–138 t ha^{-1} for natural hardwoods. Planted white spruce (*Picea glauca* (Moench) Voss) and natural sugar maple and yellow birch sequestered the most C. The total C (above and belowground biomass and deadwood, excluding soil carbon) on the 428,000 ha test landbase was 35 million tonnes, or an average of 82 t ha^{-1}.

Keywords: Forest carbon; Sequestration; Timber supply models; Forest management; Indicators; Tolerant hardwood; Spruce; Balsam fir; Dead organic matter

1. Introduction

Quantification of forest carbon (C) has recently gained in importance to forest managers, largely due to the Kyoto Protocol and global warming (Kurz and Apps, 1999; Phillips et al., 2000; Sohngen and Mendelsohn, 2003; Nelson and de Jong, 2003; Baral and Guha, 2004). Increased atmospheric carbon dioxide (CO_2) is considered to be responsible for global warming and climate change (Heath and Smith, 2000; Phillips et al., 2000). Forest managers are interested in quantifying forest C stocks on their landscapes and influence of management on C sequestration (Heath and Smith, 2000; Smith and Heath, 2001).

Forest ecosystems act as atmospheric filters of CO_2. Forests sequester C from the atmosphere through the process of photosynthesis and store C in woody biomass. Mortality transfers C from biomass to forest soils, coarse woody debris (CWD), litter and other forms (Lee et al., 2002). There are opportunities to increase the amount of C in forest ecosystems through intensive management or longer harvest rotations (Hoen and Solberg, 1994; Van Kooten et al., 1995; Murray, 2000; Sohngen and Mendelsohn, 2003). Should managers choose, or be obligated, to quantify C stock changes on forest landscapes, a quantifiable measure of C is needed for integration into current management planning.

Several studies have quantified stand-level C in forested ecosystems (e.g., Granier et al., 2000; Law et al., 2001; Hazlett et al., 2005; McDowell et al., 2005; Smith et al., 2006), and others have done so at a larger regional or landscape scale (Dixon et al., 1994; Turner et al., 1995; Brown and Schroeder, 1999; Kurz and Apps, 1999; Bhatti et al., 2001; Banfield et al., 2002; Zheng et al., 2004; Fredeen et al., 2005; Liski et al., 2006). Scattered information regarding C dynamics for a limited number of stand types is insufficient to consider C

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sequestration with other management objectives in industrial forests.

Our objective was to establish a framework to generate C yield curves based on existing permanent sample plot and stand development survey data for major forest types in an industrial forest, over an entire rotation following different silviculture treatments. In particular, C yields are compared for natural versus managed and softwood versus hardwood forest. The C yield curves generated with this procedure could be directly used for C accounting under forest management scenarios, or be used to actively manage forest to enhance onsite C sequestration. C yield analysis of major forest types could assist forest managers to prioritize silviculture treatments intended to increase C sequestration, without modifying the entire forest management plan.

In this paper, we use a C simulation model to generate stand-level complete C temporal dynamics for all major forest stand types within the management zones. ''Complete C'' yields can then be used in timber supply models that can optimally time management interventions to capture stand mortality and to design sustainable resource management. Timber supply models are often flexible enough to accommodate conflicting objectives, such as managing for both timber and C through alternative harvesting scenarios. C yield data also permit calculation of the spatial distribution of C on the landscape, as a function of stand age and cover type.

We used the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3, developed from the CBM-CFS, and CBM-CFS2—Kurz et al., 1992; Kurz and Apps, 1999), stand volume yield curves, and forest inventory data to simulate living and dead C dynamics for natural and managed stand types. The objectives of this paper are to (1) develop C yield curves for living biomass and DOM pools; (2) compare C yield curves for natural versus managed, and hardwood versus softwood stand types; and (3) apply these curves to determine the spatial C distribution on a 428,000 ha Crown Forest Management Area (FMA) in New Brunswick, Canada. Our C yield curves project C content in five living biomass pools and nine dead biomass pools over a 275-year period.

In Neilson et al. (submitted for publication), we use these data in a decision-support framework to optimize timber harvesting and C sequestration planning, and evaluate a number of forest management scenarios which use the 'business-as-usual' approach as the control. Results suggested that maximizing C for 80 years would lead to a 5% forest C increase (1.67 million tonnes C across the FMA) above the business-as-usual scenario (Neilson et al., submitted for publication). Similarly, maximizing C from 2002 to 2012 would result in a 3% increase by 2012. A scenario to double the supply of softwood timber could, by 2062, increase softwood harvest by 94%, and total harvest by 47%, but would decrease the forest C pool by 9% from 2002 to 2082 (Neilson et al., submitted for publication).

2. Materials and methods

2.1. Study area

Our study area was the Upsalquitch FMA (Fig. 1), licensed to Bowater Maritimes Inc. in northern New Brunswick (47°25′–48°04′N, 65°45′–67°40′W). It includes portions of three ecoregions (Zelazny et al., 1989; New Brunswick Department of Natural Resources and Energy (NBDNRE), 1998), with 91% in the Northern Uplands, 3% in the Southern Uplands, and 6%

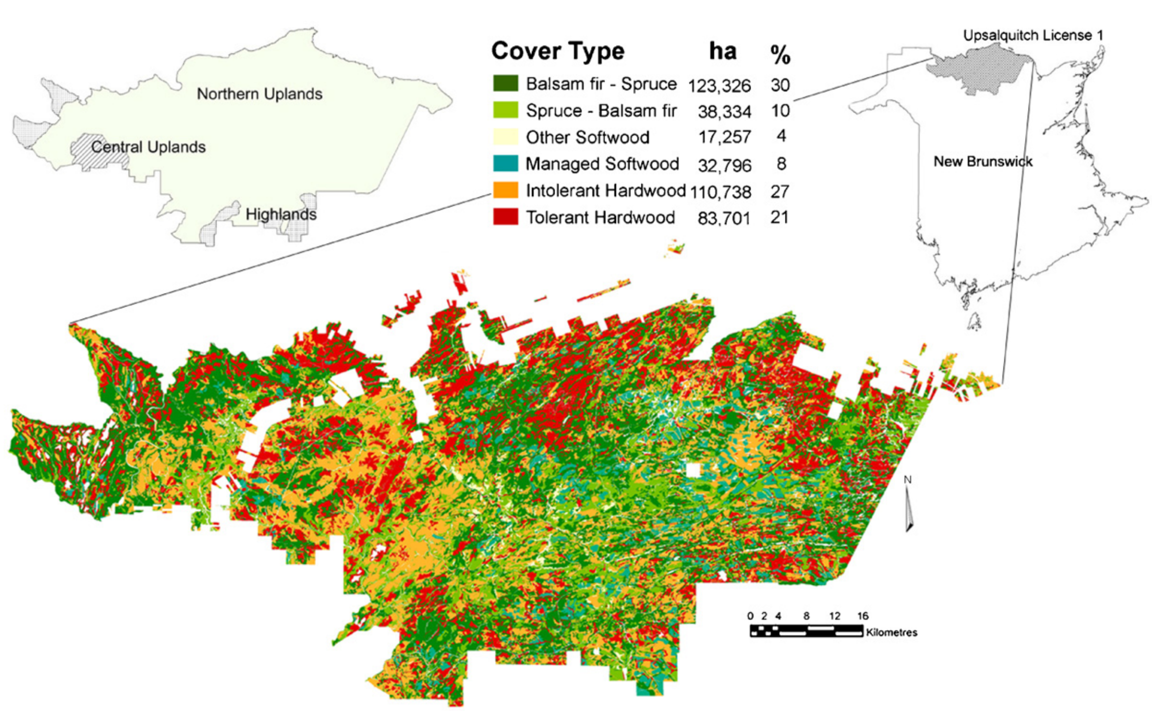

Fig. 1. Cover types of the Upsalquitch Forest Management Area with area and percent of total area listed, reference year 2002.

in the Highlands (Fig. 1). The forest is composed of softwoods, black, red and white spruce (*Picea mariana* (Mill.) B.S.P., *Picea rubens* Sarg., *Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.), jack pine (*Pinus banksiana* Lamb.), with shade tolerant hardwood ridges of American beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghaniensis* Britton), sugar maple (*Acer saccharum* Marsh.) and large quantities of intolerant hardwoods like aspen (*Populus tremuloides* Michx.) and white birch (*Betula papyrifera* Marsh.). The Northern Uplands includes intolerant hardwood stands, tolerant hardwood ridges, mixedwood areas, and spruce–fir mixes in lowlands. Eastern white cedar (*Thuja occidentalis* L.) is prevalent in the wetter zones, interspersed with areas of black spruce and jack pine on organic soils.

The Upsalquitch forest includes 411,660 ha of productive forest and 16,340 ha of roads, wetlands, or rock outcrops deemed non-productive forest area. The productive forest is divided into three management zones: (1) white-tailed deer (*Odocoileus virginianus*) winter habitat, old spruce–fir habitat, and riparian zones constituted the restricted forest (108,580 ha); (2) inaccessible forest (29,210 ha) including a protected area, ecological reserves, and private leases (sugaries, etc.); and (3) the 273,450 ha regular forest with timber production as its primary management goal. The regular forest is managed to maximize spruce–fir-jack pine volume harvested (Bowater Maritimes Inc., 2002); hardwood harvest is not maximized and was represented as a constraint in the management objective.

The forest inventory for the landbase was acquired in 1997 using 1:12,500 color aerial photography interpreted to determine stand composition, maturity, and crown closure. A sample plot network of 3573 plots was used to calibrate the photo-interpreted stands with attributes such as volume, age, and height (Bowater Maritimes Inc., 2002). The forest inventory was then digitized and input into a GIS. The company managers stratified the forest into 153 natural strata (non-treated; essentially types of stands originating before 1940) and 154 managed strata; we retained these classes to ensure compatibility of our analyses with the company management plan. After characterization, merchantable volume yield tables were developed using the STAMAN stand growth model (Vanguard Forest Management Services Ltd., 1993; Norfolk, 2005). All inventory, plot, stratification, and volume yield data were derived by the company for forest management purposes, and we retained this structure to ensure that our C analysis tools would be directly compatible with company planning databases and procedures.

2.2. Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3)

C was simulated using CBM-CFS3, version 1.0 (Kurz, personal communication), an operational-level model that uses timber volume as the independent variable for calculation of C. Parameters in CBM-CFS3 for the Atlantic Maritime, New Brunswick Ecozone, developed from the National Forest Biomass Inventory data (Gillis, 2001; Wulder et al., 2004), were used to initiate the calculation of C from volume by stand type. Belowground biomass was simulated from regression equations based upon above-ground biomass, similar to the CBM-CFS2 implementation (Kurz et al., 1996; Li et al., 2002). While documentation describing the model specifics of the CBM-CFS3 are yet unpublished, the CBM-CFS (Kurz et al., 1992) and CBM-CFS2 (Kurz et al., 1996; Kurz and Apps, 1999; Li et al., 2002, 2003) represent the modeling foundation upon which the CBM-CFS3 has been developed with many similar parameters and algorithms.

C in biomass and DOM was simulated for each stand type (management plan strata) throughout stand development for a period of 275 years, the same length of time as available volume tables. Simulations showed that soil C was stable, varying less than 5% throughout the planning horizon and the net change caused by forest harvest would be even less. For this reason, we have excluded the modeling of soil C from this study, and focused on the more dynamic live and dead organic matter (DOM) pools of C. van Kooten et al. (2004) also noted that soil C did not significantly change through forest management.

CBM-CFS3 tracks C in two major pools: (1) living biomass, calculated as a function of the growing timber volume; and (2) DOM, dependant on the stand-replacing disturbance that initiated stand development and mortality of living biomass. Quantities of CWD and DOM are initially dependant on stand history (Hély et al., 1999), with the model permitting post-clearcut, post-wildfire or post-insect disturbance origins (Kurz, personal communication), and later dependent upon stand development. Biomass simulated to have died in CBM-CFS3 initiates transfers C from the living biomass to the DOM pools. Specific parameters simulating C accumulations based on volume growth used in the model are unpublished at the time of print (Kurz, personal communication). Decay rates of the CBM-CFS2, implemented similarly in CBM-CFS3, are described by Kurz and Apps (1999) and Li et al. (2003).

In CBM-CFS3, stand growth and decline determine amounts of biomass in proportion to amount of volume, calculated by stand type from volume tables. Stand mortality is a function of change in merchantable volume over time, with mortality increasing as stands approach over-maturity (Brown and Schroeder, 1999; Taylor and MacLean, 2005). CBM-CFS3 predicts stem wood biomass from net merchantable volume, from volume tables, and then calculates biomass in other living pools, as described below. Transfers from living biomass to DOM occur based on turnover rates and upon losses in volume, similarly to the CBM-CFS2 (Kurz and Apps, 1999).

Stand origin influences initial values in DOM pools, with stands that had been clearcut before regeneration having less simulated DOM than those with wildfire as the stand replacing disturbance (Hale et al., 1999; Hély et al., 1999). Forest fires leave standing snags, while clearcut harvesting removes nearly all stemwood following harvest (Grenon et al., 2004). Within CBM-CFS3, we used clearcut events as the most recent disturbance with historical disturbance set to wildfire. This was consistent with forests in the region that have undergone interventions for the past 200 years (Erdle and Pollard, 2002) as well as cyclical spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks (Baskerville, 1995).

2.3. Biomass and DOM pools

C in woody biomass in CBM-CFS3 is divided into six pools, similar to the CBM-CFS2 (Kurz and Apps, 1999; Li et al., 2002): (1) merchantable stemwood, calculated as a function of timber volume; (2) foliage, calculated based on merchantable stemwood; (3) other biomass (bark, branches, and stumps) of merchantable trees; (4) other biomass of subordinate species, calculated as a function of timber volume; (5) fine roots (<5 mm diameter), calculated from aboveground biomass; and (6) coarse roots, calculated from aboveground biomass. Hardwood biomass has higher wood density, as reflected in CBM-CFS3 volume to biomass equations (Brown, 2002; Kurz et al., 2002).

C in CWD and DOM in CBM-CFS3 is divided into nine pools, an increase from four pools in CBM-CFS2 (Kurz and Apps, 1999): (1) CWD, the ‘‘medium’’ DOM pool, simulated from stand-replacing disturbance and fall-down of snag stems; (2) forest floor litter, the aboveground ‘‘very fast’’ pool, calculated from turnover rates of foliage and fine roots; (3) mineral soil detritus, the belowground ‘‘very fast’’ pool, calculated from turnover of fine roots; (4) mineral soil detritus, the belowground ‘‘fast’’ pool calculated from turnover of coarse roots; (5) forest floor detritus, the aboveground ‘‘fast’’ pool, calculated from turnover of coarse roots, and fall-down of snag branches; (6) and (7) C in hardwood and softwood snag stems, calculated from death of merchantable stemwood; and (8) and (9) C in hardwood and softwood snag branches, calculated from turnover of branches. Volume tables provide the independent variables, decay factors applied to each of the DOM pools initiate transfers of C to the atmosphere, and turnover rates initiate transfers from biomass and DOM pools to other DOM pools in the CBM-CFS3, similar to the CBM-CFS2 (Kurz and Apps, 1999). Two additional DOM pools, the aboveground and belowground slow DOM pools were omitted from our analysis because they represented forest soil organic matter and varied little.

2.4. Carbon yield curves

Volume yield tables from each stand type were collated into a database delineated by hardwood and softwood volume, stand type, and age class. One hectare of each stand type was simulated from age 0 to 275 years. Volumes from each species cohort within each stand type were sorted and the species with the highest merchantable volume between 40 and 80 years old was assigned as the dominant species or species group (e.g., balsam fir or balsam fir–spruce). This was used to select the ‘‘leading species’’ parameter in CBM-CFS3, which determines parameters for use in biomass equations (presently unpublished; Kurz, personal communication) used to simulate C from volume. Mixedwood strata, defined as <75% volume as softwood and <75% volume hardwood, were identified as ‘‘mixedwood’’. The C in the 14 biomass and DOM pools was summed by 5-year age class to derive C yield curves by age; 5-year classes were selected for consistency with forest management planning for the test landbase.

2.5. Modeling and mapping forest carbon

The C yields were then input to an existing timber supply model, in our case Woodstock (Remsoft, 1999). Neilson et al. (2006) described application of the modeling framework using C yields to simulate effects of forest management on C stocks. In this paper, we used the C yield curves to derive spatial distribution of C for the reference year 2002. The GIS shapefile of the forest management area included cover type and age class attributes for each stand polygon. C yields by stand type and age class were imported into the GIS, and we did a ‘thematic join’ of stand type identifiers in the cover type attributes table to those in the C yields table, to look up C as a function of stand type and age class.

The advantages of this method, in comparison with using the static current forest inventory to estimate C, is that (1) C is projected over a full 275-year period, enabling future projections and analyses of alternative management scenarios (Neilson et al., submitted for publication); and (2) we incorporate an estimate of the amount of DOM in stand types dependant on stand initialization and past disturbance regimes. An alternative might be to use a single biomass expansion factor applied to generic stand types and the static current inventory, but our method uses the functionality of CBM-CFS3 to simulate C based explicitly on the volume of specific stand types. C yield curves permit incorporation of C stock estimation into forest management planning.

3. Results

3.1. Living biomass pools C in natural and planted stand types

Forty percent of the test landbase was covered in a variety of balsam fir, fir–spruce, or spruce–fir stand types, deciduous stand types comprised 48%, and other softwood stands (eastern white pine, red pine, and eastern white cedar) made up 4% (Fig. 1). Many of the 300 plus stand types used in management planning are variants of species groups by ecosite or silvicultural treatment. In this paper, we present C yield curves in living biomass pools in six natural and four planted stand types (Fig. 2). In balsam fir and black spruce–balsam fir stands, 40–50% of total C and 54–58% of the living biomass were in merchantable stemwood, once the stand reached maturity (Fig. 2a and b). Rate of stand decline after maturity varied among stand types, with balsam fir showing a rapid decline in stemwood C after year 80, as opposed to decline beginning around age 100 in black spruce–balsam fir (Fig. 2a and b). Cedar stands showed similar distribution of C to black spruce–balsam fir, but with a longer period of regeneration delay and decline in stemwood C only after 125 years (Fig. 2c). Hardwood stands included 21% of the landbase in shade tolerant sugar maple, yellow birch, and American beech, and

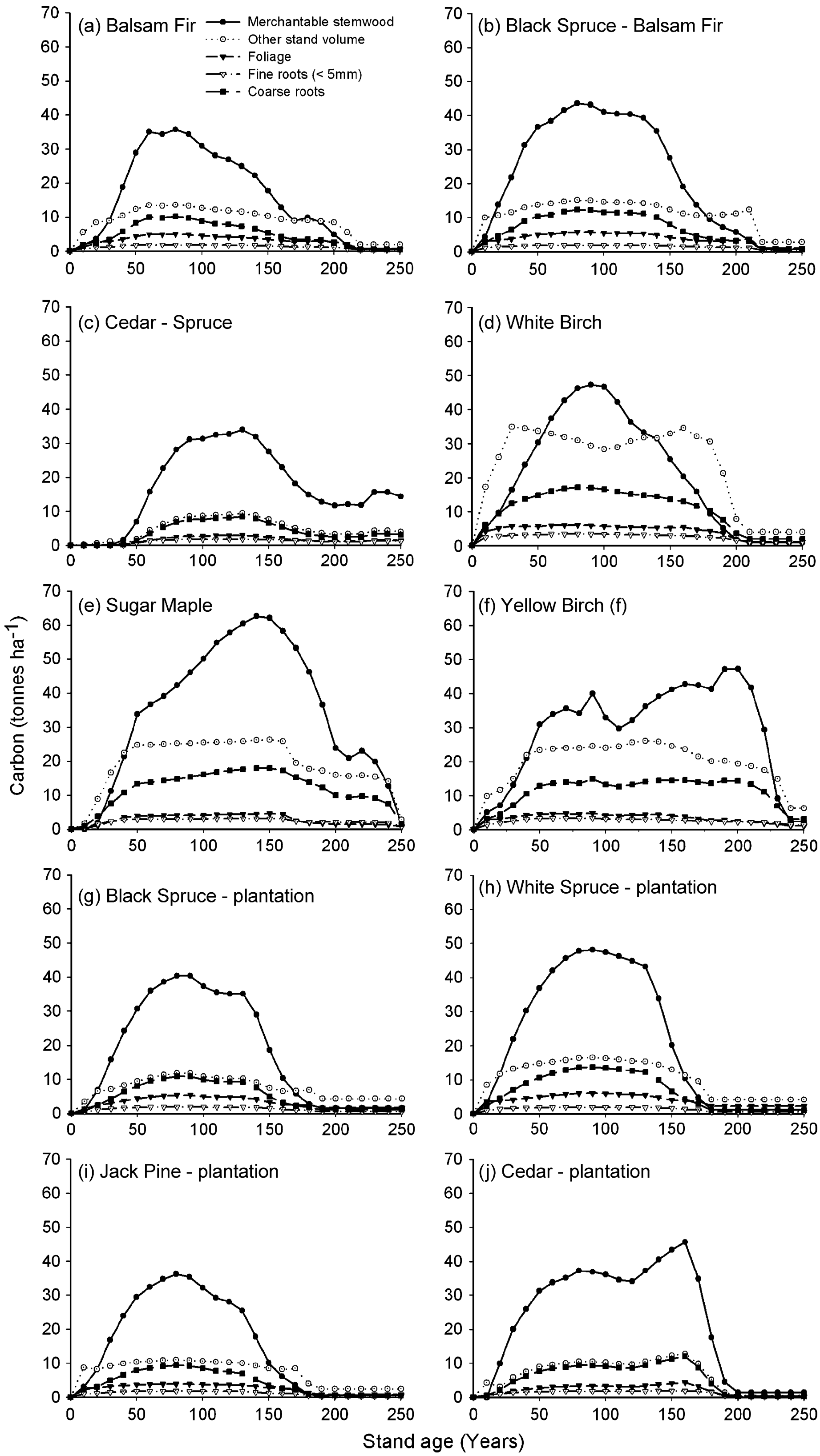

Fig. 2. C in living biomass pools in six natural and four planted stand types, as simulated by CBM-CFS3 for 250 years. These represented post-clearcut stands with a historic disturbance regime of wildfire, and cover most of the spruce–fir and hardwood stand types on the landbase. Flat lines at the end of g, h, i, and j represent periods where zero merchantable volume was simulated by the STAMAN stand growth model.

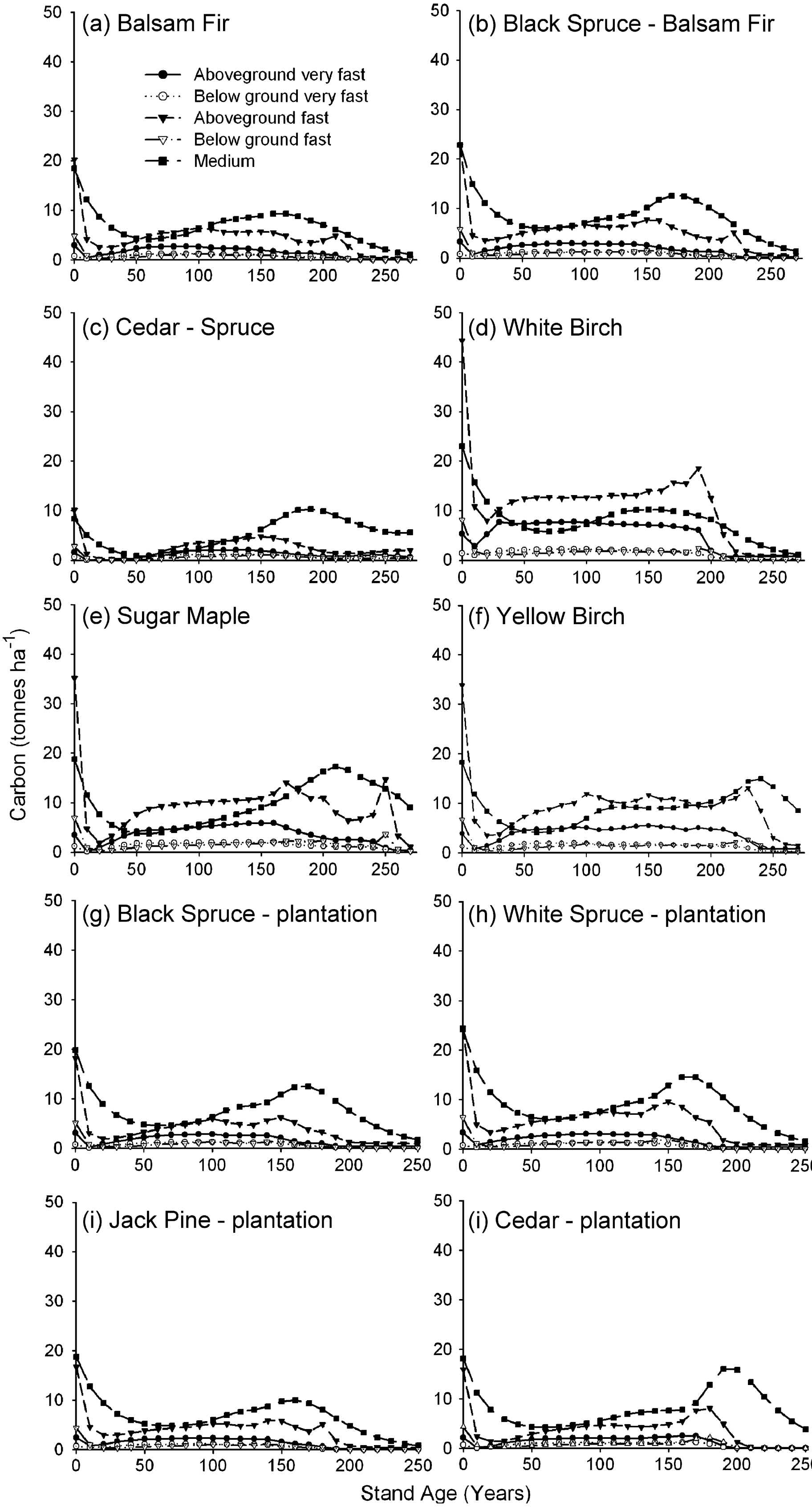

Fig. 3. Carbon simulated in dead organic matter pools in 10 natural and planted stand types on the Upsalquitch Forest Management Area.

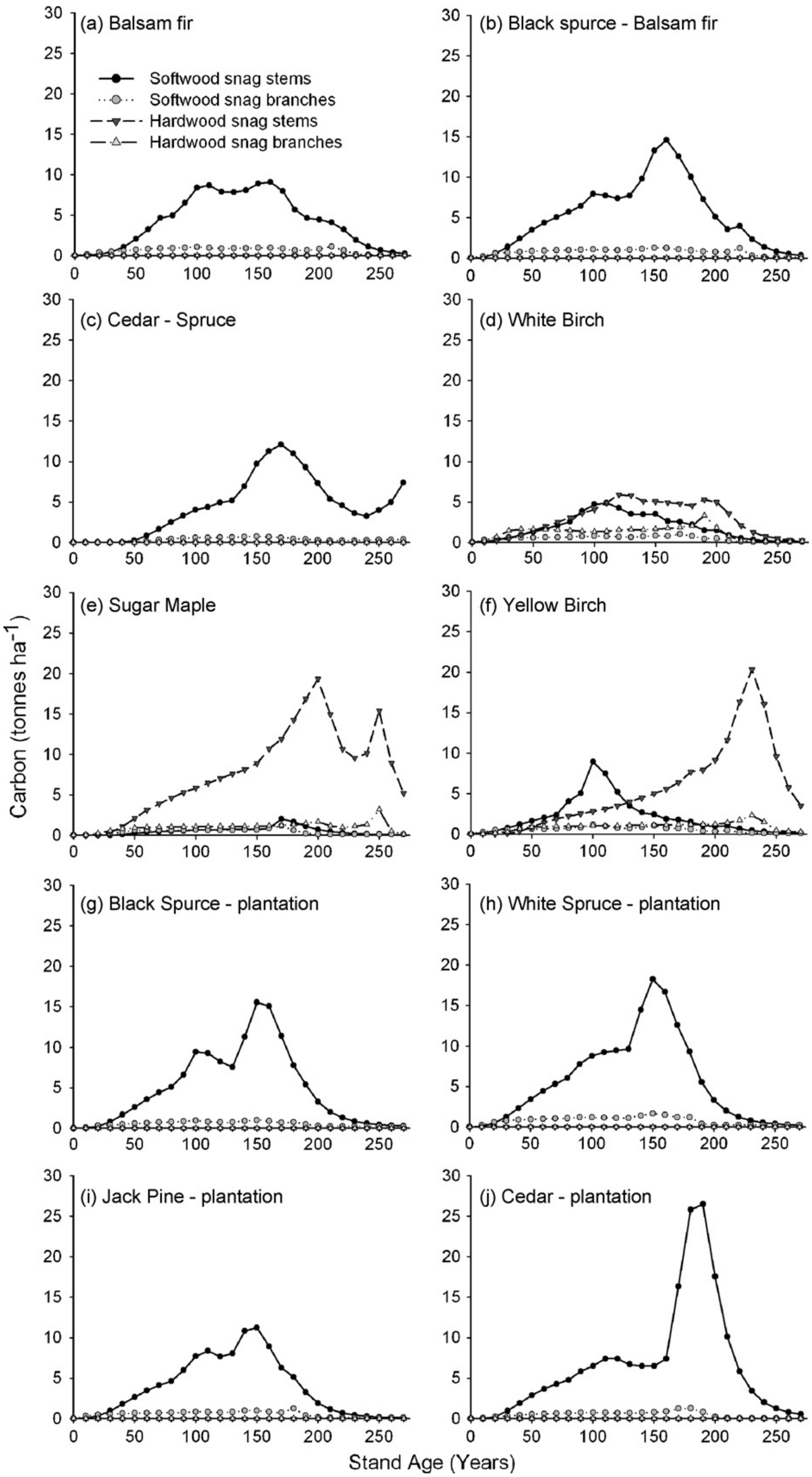

Fig. 4. Carbon simulated to accumulate in snags in six natural and four planted stand types on the Upsalquitch Forest Management Area.

27% in intolerant white birch, red maple and poplar. Tolerant hardwoods were longer lived and maintained stemwood C 50–100 years longer than softwoods (Fig. 2e and f). Simulated hardwood stands also had 22–47% more total C in biomass than did softwood stands.

Planted stand C yield curves followed similar patterns to natural stands, but generally with less ‘other stand volume’ C, since >75% was typically in planted species, and with most C in merchantable stemwood at maturity (Fig. 2g–j). Plantations had peak C at about year 100, with values of 110–150 t ha^{-1} and 70–73% of C in living biomass and 39–41% in merchantable stemwood. At age 50, plantations reached their economically optimal age for timber volume, but showed less C, 80–104 t ha^{-1}, than at the peak, with 73–75% of the C in living biomass and 38–42% in merchantable stemwood. Between ages 50 and 100, volume growth slowed and more DOM accumulated. Natural stand types tended to have more variable ages of peak C, depending upon species, with some peaking at age 130 and others at age 80, with ~70–75% of the C in living biomass and 35–45% in merchantable stemwood.

3.2. DOM pool C in natural and planted stands

In the first 20 years following post-clearcut stand initiation, DOM pools contained most (75–100%) stand C (Fig. 3), as a result of decomposition of organic matter left post harvest. Also, as timber volume declined in old stands, C transfer from living biomass to DOM pools increased. The cedar–spruce stand type had the least DOM following clearcutting, with only 3 t ha^{-1} at age 50, compared to 20 t ha^{-1} in sugar maple and yellow birch stand types (Fig. 3). Stands generally had the least DOM between ages 40–60 years, at 13–20 t ha^{-1} in spruce–fir and balsam fir versus 18–38 t ha^{-1} in sugar maple, yellow birch, and white birch stands. Minimal DOM coincided with peak C in the merchantable stemwood in the fir and spruce–fir stand types (Figs. 2 and 3). White birch was simulated to have the most DOM throughout stand development, at an average of 38–40 t ha^{-1} (Fig. 3). DOM C in planted stands (Fig. 3g–j) ranged from 48 to 64 t ha^{-1} following stand initiation, and, following stand decline, peaked at 29–40 t ha^{-1} at age 160 years in planted spruce, jack pine and cedar.

C in snags generally appeared after age 40 years in natural stands, but peaked at ages 90–120 years for balsam fir and white birch, 150–160 years for black spruce and cedar, and at 200–225 years for sugar maple and yellow birch (Fig. 4). Quantity of snags was highly dependant on stand volume and stand type, with tolerant hardwoods having maxima of 25–35 t ha^{-1} versus 12–18 t ha^{-1} in fir and spruce–fir types. Planted stands also generated C in softwood snags, peaking at about age 150 for spruce and jack pine, and 195 years for cedar. Snag branches accounted for only 3–4 t ha^{-1} of C in the four planted stand types (Fig. 4). During stand decline, the C in merchantable stemwood was transferred to snag pools (Figs. 2 and 4). Snag dynamics in yellow birch stands (Fig. 4f) reflect mortality of early successional softwoods at about year 100, resulting in 4–10 t ha^{-1} of softwood snag stem C, and decline in merchantable stemwood C after age 200 years, when snag stem C increased

Table 1
Mean carbon by stand type, ecoregion, and three broad age classes

Stand types	Carbon (t ha^{-1}) by ecoregion[a] and age class[b] (years)								
	Highlands			Northern Uplands			Central Uplands		
	0–40	41–80	81+	0–40	41–80	81+	0–40	41–80	81+
Balsam fir–spruce	45.2 ± 0.6 (384)	85.7 ± 0.3 (1690)	88.4 ± 0.5 (310)	40.1 ± 0.3 (2248)	82.8 ± 0.07 (17018)	87.6 ± 0.2 (3132)	48.6 ± 2.8 (19)	89.2 ± 0.4 (364)	94.1 ± 1.0 (15)
Spruce–balsam fir	38.0 ± 1.1 (91)	75.6 ± 0.98 (212)	90.0 ± 1.2 (101)	40.6 ± 0.6 (673)	78.3 ± 0.2 (4410)	85.3 ± 0.4 (1141)	43.1 ± 1.8 (68)	80.5 ± 0.5 (253)	86.0 ± 4.1 (3)
Intolerant hardwood	59.8 ± 0.7 (1393)	108.5 ± 1.0 (313)	111.3 ± 6.0 (12)	51.3 ± 0.2 (11353)	114.5 ± 0.2 (8178)	122.0 ± 0.5 (500)	51.7 ± 1.9 (101)	116.8 ± 0.8 (485)	–
Tolerant hardwood	44.2 ± 1.7 (131)	114.1 ± 0.3 (600)	130.9 ± 0.8 (163)	49.4 ± 0.4 (2835)	114.2 ± 0.2 (9048)	142.3 ± 0.4 (2288)	68.4 ± 3.8 (16)	115.1 ± 1.5 (116)	–
Other softwood[c]	42.9 ± 3.9 (11)	45.9 ± 3.3 (34)	71.8 ± 2.3 (65)	35.2 ± 1.6 (140)	46.5 ± 0.6 (1219)	71.0 ± 0.3 (2206)	–	40.7 ± 2.3 (41)	71.5 ± 0.8 (10)
Plantation[d]	35.0 ± 0.2 (658)	–	–	34.4 ± 0.1 (5576)	–	–	36.0 ± 0.0 (56)	–	–
Pre-commercially thinned[d]	40.7 ± 0.7 (333)	–	–	40.6 ± 0.3 (2020)	82 ± 0.0 (2)	–	48 ± 0.0 (2)	–	–
Multi-aged[e]	–	–	96.6 ± 0.3 (25)	–	–	103.7 ± 0.5 (380)	–	–	–

Note: Mean ± 1S.E. are presented. Values in parentheses give the number of stands used in calculation of the mean.
[a] Ecoregions delineate areas of similar species composition and growing conditions.
[b] 5-year age classes.
[c] Other softwood includes eastern white cedar, eastern white pine, red pine and jack pine.
[d] Aggregated in Fig. 1 as managed softwoods.
[e] Aggregated in Fig. 1 with tolerant hardwood.

from 8 to 20 t ha^{-1} (Fig. 4f). Snags made up about 10% of the total C within stands, averaging 8 t ha^{-1} across all ages in planted stand types and peaking at ~35 t ha^{-1} in 200-year-old yellow birch and sugar maple stands.

3.3. Spatial carbon distribution

Stand age and species composition clearly influenced the amounts of C in stands. We summarized C content within three broad age classes, 0–40, 41–80, and 81+ years, representing regeneration-immature, maturing, and overmature development phases. Balsam fir–spruce stands in three different ecoregions averaged 40–49, 83–89, and 88–94 t ha^{-1} at ages 0–40, 41–80, and 81+, respectively (Table 1). Balsam fir stands made up 30% of the area and also 30% of the total C on the landbase (Fig. 5). Spruce–fir stands generally had less C than balsam fir–spruce stands, averaging 38–43, 76–81, and 85–90 t ha^{-1} for 0–40, 41–80, and 81+ years, respectively. Other softwood stands consisting of mixes of eastern white cedar, hemlock and red, white and jack pines made up 4% of the landbase in area yet only 3% of the total C.

Intolerant hardwoods made up 27% of the landbase area and 28% of the total C. Intolerant hardwood stands generally had higher mean C per hectare than softwoods, ranging from 51 to 60, 109 to 117, and 111 to 122 t ha^{-1} for ages 0–40, 41–80, and 81+ years (Table 1). Tolerant hardwoods made up 21% of the landbase area yet 26% of the total C. Tolerant hardwoods showed higher density of C per hectare than other stand types, at 44–68, 114–115, and 131–142 t ha^{-1} for ages 0–40, 41–80, and 81+ years.

Plantations were young (mean age of 9 years) and thus had relatively low C, ranging from 34 to 36 t ha^{-1} across ecoregions (Table 1). Precommercially thinned stands (mean age of 21 years) had higher mean C at 41–48 t ha^{-1} (Table 1). Managed softwood made up 8% of the area yet only 4% of the total C, due to their young ages. Multi-aged stands, generated by selective harvesting, included sugar maple and yellow birch aged 81+ years old, with 97–104 t ha^{-1} of C (Table 1). Multi-aged stands were aggregated into the tolerant hardwood group (Fig. 1), which contributed 26% of the total C on the landscape.

The mapped distribution of C in stands across the landbase is shown in Fig. 5. Tolerant hardwood and old stands had the most C. The total C (above and belowground biomass and CWD) on the 428,000 ha landbase was 35,040,000 t, or an average of 82 t ha^{-1}. Totals of 58,460, 115,200, 170,000, and 68,000 ha contained 0–40, 41–80, 81–120, and 121+ t ha^{-1}, respectively (Fig. 5). Managed and unmanaged softwood forest concentrated in the central part of the landbase (Fig. 1) is evident as relatively low C areas (Fig. 5).

4. Discussion

4.1. Species influence on C

Due to differences in wood density, the amount of C was higher in hardwoods than in softwoods at ages 40 and greater (Table 1). We compared our results to those of other studies in comparable stands types, essentially as a ‘‘verification’’ of parameters used in CBM-CFS3. Shade tolerant hardwoods generally contain more C than softwood stand types of similar volume and age (Jenkins et al., 2003). Yellow birch stands in our study area had about 40 t ha^{-1} more C than spruce–fir stands at age 150 years. Brown (2002) found that softwood and hardwood forests averaged about 25–75 and 40–90 t ha^{-1} of C, excluding roots; our results, excluding roots, which averaged 10–20 t ha $^{-1}$of C at age 80, were similar for softwoods and higher at 44–142 t ha^{-1} for hardwoods. Zhou et al. (2004) found average above and belowground biomass of 96 t ha^{-1} in spruce stands with an average of 174 m^3 ha^{-1}, similar to our results of 86–90 t ha^{-1} in spruce–fir stands aged 81+ years.

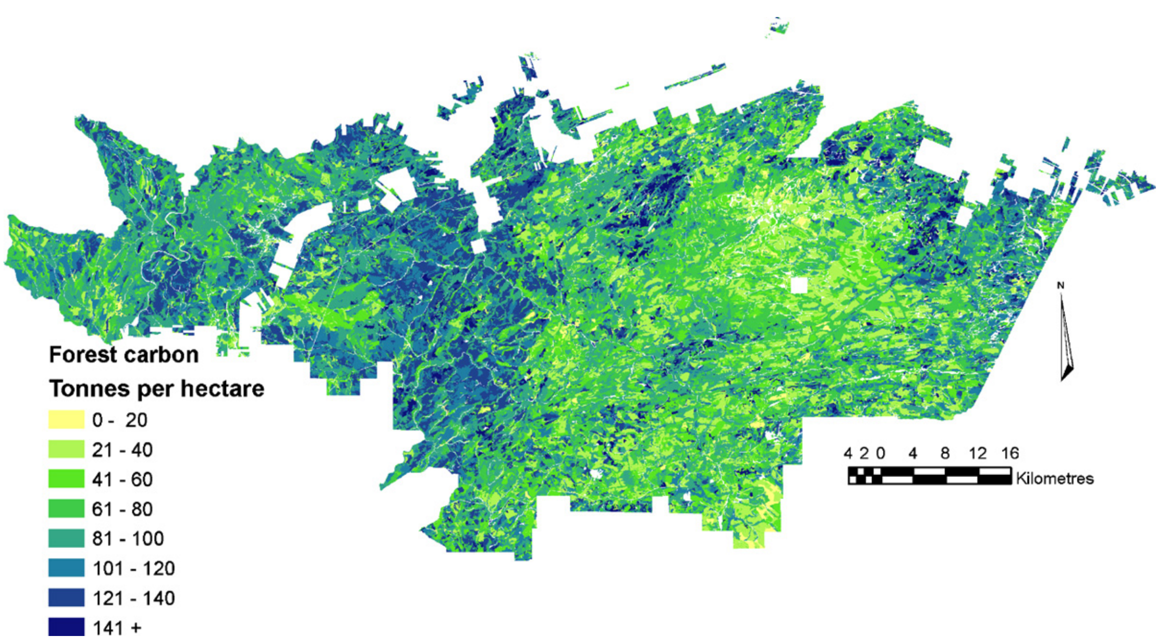

Fig. 5. Spatial distribution of forest C stocks on the Upsalquitch Forest Management Area.

Smith et al. (2006) calculated 97 t ha^{-1} of biomass C at age 85 with 171 m^3 ha^{-1} in spruce–balsam fir stand types; our average of 87 t ha^{-1} was comparable.

Spruce-dominated stands in Ontario, Canada had 18–20 t ha^{-1} of C in belowground biomass and 87–89 t ha^{-1} of C in aboveground biomass (Hazlett et al., 2005), versus 75–90 t ha^{-1} for similar stands in our study. C in snags, at 5–7 t ha^{-1} (Hazlett et al., 2005) was also similar to our results. Snag basal area ranging from 8 to 15% of the total basal area of live trees (Goodburn and Lorimer, 1998) was comparable to the 9–11% of the stand total C based on proportion of snags to live tree C (stemwood, foliage and bark) in our hardwood stands.

Ecoregion had a minor influence on mean C per hectare, which was consistently highest in the Central Uplands ecoregion, though not a statistically significant difference. This was most likely due to increased volume in stands within this ecoregion. Taylor and MacLean (2005) studied decline of balsam fir and spruce in permanent sample plots in the same three ecoregions in our study, and also determined that volume was highest in plots in the Central Uplands.

4.2. Age class influence on C

Among all stand types, total C in all biomass pools ranged from 50 to 109 t ha^{-1} at age 50 years, 92–138 t ha^{-1} at age 100, and 79–145 t ha^{-1}at age 150 years. At age 100 years, planted softwoods had 94–135 t ha^{-1}, versus 92–117 t ha^{-1} for natural softwoods and 127–138 t ha^{-1} for natural hardwoods. Planted white spruce and natural sugar maple and yellow birch clearly sequestered the most C. As stands age, they accumulate more C. Stands aged >80 years had mean total C 13–25% higher than stands aged 0–40, and 1–11% higher than stands aged 40–80 (Table 1), similar to other results (Hale et al., 1999; Means et al., 1999; Siitonen et al., 2000). However, after stand break up, timber volume and C began to decline. Decline in older fir–spruce stands occurs quickly (Taylor and MacLean, 2005) and reductions in C coincide with reductions in mean annual volume increment. Total C in fir–spruce and spruce–fir stands associated with volume decline (Fig. 2a and b) decreased by 8–10% in 20 years, 19–21% in 40 years, and 47–66% in 100 years. Other research has shown a constant rate of growth with increasing stand age (Zhou et al., 2004) with no decline in C. However, in New Brunswick, especially in relatively short-lived balsam fir, stand break up seems to be a driver of successional stand development (Taylor and MacLean, 2005). When stands enter a steady state in which the rates of growth and death are equal, CWD accumulates (Hagan and Grove, 1999). Our results reflect substantial snag and DOM associated with natural spruce–fir decline.

4.3. Carbon yield curves

Our approach to developing C yields for forest stands differs from that of previous studies that used biomass expansion factors to convert measured static timber volume to tonnage of C (Brown and Schroeder, 1999; Heath and Smith, 2000; Smith and Heath, 2001; Liski et al., 2006). For example, Liski et al. (2006) used successive amounts of volume estimated from forest inventories collected over the past 80 years, and converted volume to C. Whereas the ''inventory'' approach sums C across temporal scales by comparison of total volume in each inventory year, we used a method analogous to timber supply projection for annual sustainable harvest calculation for large landbases, in which plot data were used to parameterize volume growth for all classes of stands ('strata') in the forest management unit. Instead of timber volume yield curves, these were C yield curves that simulate C growth and decline by stand type. The CBM-CFS3 does not use biomass expansion factors, and instead relies on volume to biomass conversion equations developed from studies on similar sites (Kurz et al., 1992). Our approach differs from previous studies in using CBM-CFS3 as a tool to derive C yield curves, which then can be used as input into a timber supply model, to provide managers with a dynamic view of effects of silviculture and harvesting plans on forest C. This method to generate C yields is transferable to other areas, given stand growth and yield data. The CBM-CFS3 model can be parameterized to simulate C dynamics throughout the forests of Canada.

C yield tables have been proposed to quantify landscape-level C (Smith et al., 2006), but to our knowledge, not yet incorporated into a current operational forest management plan. Remote sensing (e.g., LIDAR) has been used to estimate aboveground biomass (Bergen et al., 1998; Means et al., 1999; Patenaude et al., 2004), though it requires additional data collection and considerable data processing and analysis. Forest inventory data presently exist in most jurisdictions, and growth and timber yield are regularly estimated as part of forest management planning. Our method builds upon this existing data and timber supply analysis procedures. C yield curves for different stand types help identify areas with high concentrations of C (Fig. 5).

4.4. Application of the framework

The results presented in this paper were from a case study of an actual forest management plan, in cooperation with forest industry in northern New Brunswick. While the results are specific to the landscape studied, the modeling framework is applicable to any forest area under similar management planning systems. Management plans beginning with sample plot data summarized and collected in stand growth tables and ending with sustainable harvest level calculation with a timber supply model are compatible with the C modeling framework presented in this paper. Simulation of C stocks using merchantable volume as the independent variable is possible following the methods explained above. Certainly the number of forest strata and complexity of forest areas will differ regionally. Our main assumption is that stand growth and yield values per ha are adequate representations of current, past and future productivity of the forest. C yields can then be used as inputs to a timber supply model as essentially a crop yield of C per stand type analogous to timber volume.

Timber supply models including C estimates can take advantage of optimization technologies to reduce opportunity costs of timber harvesting while maintaining C stocks on the landscape (Neilson et al., submitted for publication). This analysis method will allow forest managers to construct management plans that balance two objectives, timber extraction and C storage. Methods proposed by Smith et al. (2006) are also applicable though they do not take advantage of methods of simulating C stocks from volume in CBM-CFS3.

4.5. Management implications

The issue of C sequestration by forests is currently receiving much attention as a means to mitigate increasing CO_2 concentration in the atmosphere. The method in this paper has two advantages: (1) it can be implemented in an intuitive manner into existing forest management plans, and thus is more apt to be used by managers; and (2) it accounts for residence time of sequestered C. Modeling C residence times is crucial, since forests do return C to the atmosphere on time scales of several decades to centuries, depending upon management regimes. The economic value of planting forests depends upon both amount of C sequestered and its residence time. It is clear that older forest stands accumulate and store more C than younger stands. Stand age also strongly influences harvest scheduling, which often focuses on ‘‘oldest first’’ in spruce and fir stands in New Brunswick. This results in a conflict when forest C is a management objective. Obviously managers would choose to harvest stands before decline begins to impact timber volume, but this may sacrifice forest structures such as snags and CWD that are needed for ecological values. Until now, managers would only have a reference to the amount of timber lost during the decline phase of forest stands, but with C yield curves, they can formulate a trade-off analysis to compare volume lost and C stored, and use timber supply model optimization to schedule harvesting to influence both timber and C sequestration.

Managing for more hardwood species may be an option if managers wish to increase the amount of C on the landscape. Pulp mills in New Brunswick, which have focused on softwood pulpwood, are being rendered less competitive in the global forest product market. A focus on value-added hardwood products would mean a management focus on developing higher-quality hardwood logs. This would mean increased multi-aged, selective harvest hardwood management, which leaves more C in the forest as compared to short rotation management (Hazlett et al., 2005). More hardwood would make for more C, in general. This may or may not be feasible, but if hardwood management results in increased C stocks, managers could qualify for C emissions offsets.

If guidelines for managing forest C stocks are imposed upon forest managers, then a method to quantify C stocks is needed. Until now, quantification of C stocks on industrial forested landscapes was only conducted by research scientists. The method to calculate stand-level C yields in this paper takes advantage of existing data without having to resort to costly alternatives such as LIDAR or rigorous field sampling. Using LIDAR to quantify forest biomass stocks is an additional expense in cases where field data have already been collected. Developing estimates from volume yield curves provide a twofold use of field data, for calculating timber volume and extrapolating volume to forest C.

5. Conclusions

Hardwood stands contain 10–20% more C per hectare than softwood stands with similar volume. Generally, tolerant hardwood stands showed greater potential to act as reservoirs of C than intolerant hardwood or softwood stands. The mean C in tolerant hardwoods aged ≥80 years was 130–142 t ha^{-1}, versus 88–94 t ha^{-1} in balsam fir–spruce stands. Most plantations in New Brunswick are still too young to evaluate the effectiveness of increased intensive management to promote more C storage. Multi-aged hardwood management has generally high C content (∼100 t ha^{-1}), and more of it would increase forest C.

We used growth and yield data from a forest management timber supply model used in strategic and tactical planning. Our method of generating C yields is transferable to other timber supply models that use volume over age curves, and both spatial depiction of C on a forest landscape and scenario planning of alternative future management regimes are possible given these stand C yields. The development of C yield curves permits spatial C modeling using timber supply modeling tools. Since timber supply models already use available forest inventory data, this forms a natural progression to including C in integrated forest management plans.

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