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Biomass and Carbon Dynamics in Forest Management at a Strategic Scale

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ABSTRACT

This study explored these two questions: (1) How much carbon can be stored in the forest? and (2) Which forest management regimes best achieve the dual objectives of high sustained timber yield and high carbon sequestration? A model that can be used to predict carbon sequestration potential within a forest region assuming a given management strategy was developed. First, a carbon sequestration unit that accounts for both the amount of carbon stocked and the time during which it is stocked was introduced. This unit was used to integrate the carbon dimension in a Model-III formulation for forest management adapted from the description of models used by the Chief Forester who is responsible of determining the annual allowable cut in the different forest management units in Québec. The CBM-CFS3 model was used to simulate carbon dynamics of above- and belowground biomass and dead organic matter, including soils. Different management scenarios were developed using the data of an actual forest management unit in Quebec. Managing this forest for carbon maximization instead of letting grow naturally with no harvest or other treatment, would increase the carbon stocks by 1.89%, and only 25% of the carbon stock is estimated to occur in the aboveground live pool. Six scenarios aimed at achieving the dual objectives of high sustained timber yield and high carbon storage were also computed and compared.

Keywords: Carbon sequestration, forest biomass, annual allowable cut, sustainable forest-management, strategic planning.

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Introduction

Carbon is present in the natural environment in many forms. In the air, it is present as carbon dioxide. The concentration of carbon dioxide in the atmosphere is known to contribute to the greenhouse effect and global warming (Cox et al. 2000). Efforts are being made to reduce the amount of carbon dioxide in the atmosphere to counter this effect. Much of these efforts involve the forests because they can be huge stores of carbon (Bersteiner et al. 2005). Indeed, the forest ecosystem is considered as a system of pools with the capacity to accumulate or release carbon. Live biomass, soil, and dead organic matter are three general carbon pools in forests (IPCC, 2003). Large amounts of carbon can move from one pool to another. In the forests, carbon in the atmosphere is used in photosynthesis to create new plant material. Over time, these plants die and decay, are harvested by humans, or are burned either for energy or in wildfires. The periods of carbon sequestration by net storage in the different carbons pools in the forest can range from years to centuries with the time scale dependent on species, site conditions, disturbance, and management practices (Dixon et al. 1994). Boucher et al. (2012) have gone so far as considering that some forest management activities qualify as "negative emission technologies" providing that part of the carbon sequestered in the different forest pools is indefinitely stocked in both on-site and off-site carbon pools i.e. in harvested wood products. While all the forest-management activities aimed at increasing carbon stocks are common practices that are technically feasible, the extent and area over which they are implemented is very limited (Metz et al. 2007).

For years, forests have been managed primarily for the long term supply of timber products. In Canada, for instance, the provincial governments uses strategic models to look at the possible impacts of today's harvesting practices on public forest 100 to 200 years in the future. These models have been on a formulation that could be used to decide on (i) the annual amounts of timber that can be harvested on a sustainable basis (referred to as the Annual allowable cut or AAC) within defined forest areas, and (ii) the types of management actions or silvicultural treatments for regenerating the harvested forest (what treatments, in which stand types, and when to carry them out). Such decisions are typically made and implemented at the scale of Forest Management Units (100 000 to 10 000 000 ha), however, their impact on carbon sequestration in forests was simply not considered. Already since 2002, Kurz et al. (2002) alleged that "forest management activities, implemented at the operational scale, can have significant impacts on the carbon budget of Canada's forests at the operational and regional scale, and the cumulative effects can be of importance to the national net balance of greenhouse gas sources and sinks". From there, it become clear that any model for strategic forest management should include detailed modelling of the carbon dynamics in the forest ecosystem.

Several initiatives to couple models for strategic management to models of the carbon dynamics in forests have emerged in the research literature. Table 1 summarizes the most pertinent contributions. The modelling objectives and intended uses differed. In brief, scenarios of timber management scenarios were combined with and carbon sequestration in forest (Meng et al. 2003; Bourque et al. 2007; Hennigar et al. 2008; Gharis et al. 2014) was combined with net revenues from wood products (Bourque et al. 2007), wood products carbon inventory with consideration of avoided emissions from product substitution (fossil fuel) (Hennigar et al. 2008; Gharis et al. 2014), and soil expectation value (Gharis et al. 2014). When the optimized function contains multiple conflicting objectives, the resolution scheme employed became more sophisticated, such as in Bourque et al. (2007) and Gharis et al. (2014).

Table 1. Comparison of initiatives to couple models for strategic management to models of the carbon dynamics in forests

	Modeling objective	Resolution scheme	Wood supply projections generation model	Carbon stock calculation model	Forest data	Simulated time horizon
Meng et al. 2003	To assess carbon sequestration resulting from specific forest-management scenarios.	Procedural steps	Using the Staman stand management growth and yield model (New Brunswick Dept. Nat. Res.) in conjunction with the Woodstock™ spatial planning system.	Multiplying a series of simple wood volume-to-C conversion factors to wood supply projections	105,000 ha special management area	80 years
Bourque et al. 2007	To achieve specific target values of net revenues from wood products and levels of stored carbon in the landscape with specified priority levels.	Goal programming		Multiplying a series of simple wood volume-to-C conversion factors to wood supply projections.	A 53,000 ha zone within a 110,000 ha forest	80 years
Hennigar et al. 2008	To maximize total forest and wood products carbon inventory with consideration of avoided emmissions from product substitution.	Multiobjective Linear program		Using the CBM-CFS3 for forest carbon, and direct conversion of merchantable harvest volume for product carbon.	30,000 ha hypothetical forest	300 years (results limited =< 250 years)
Gharis et al. 2014	To investigate optimal stand level management with competing objectives of maximizing soil expectation value, carbon storage in the forest, and carbon dioxide emission savings from product storage and substitution**.**	Compromise programming	Using the NCSU growth and yield simulator (integrated in a non-linear optimization problem that is solved using the Microsoft solver).	Multiplying a series of simple wood volume-to-C conversion factors to wood supply projections.	1 acre	100 years

Added to this is the difficulty to determine appropriate values for different functions parameters (suitable cost coefficients and penalties, reasonable products prices, achievable targets, meaningful priorities for objectives, etc.). The values of these parameters will depend on several factor including the forest region, the socio-economic priorities of the regions involved, the overall economic environment, etc. From a strategic forest management perspective, it may be irrelevant to emphasize combinations of aspects such as net revenues from wood products, product carbon and substitution of products/fuels in the optimization models. We believe that, strategic forest management should aim at maintaining the processes for carbon uptake and storage within the natural range of variation. In fact, government agencies and land managers need to focus on the forest and ensure its sustainable management. They need to simultaneously optimize the forest carbon pool and the production of forest products. Then, it is up to the transformation industries to look closely at the markets conditions (including the carbon market) and decide on the end-use of these products.

To calculate carbon sequestration, Meng et al. (2003), Bourque et al. (2007), and Gharis et al. (2014) used a method that could not consider the variability of the carbon dynamic at the landscape (such as different forest types, terrain conditions, climatic zones, disturbances). A similar model was used by Hennigar et al. (2008) to calculate product carbon. However, these authors used the CBM-CFS3 model for forest carbon. CBM-CFS3 is a generic modelling framework with explicit simulation of carbon dynamics of above- and belowground biomass and dead organic matter (DOM), including soils, and can represent both stand- and landscape-level forest dynamics (Kurz et al. 2009). It models the fluctuation in carbon stocks resulting from natural forest growth, forest management activities and natural perturbations. Carbon stock is the quantity of carbon contained in a pool. On the other hand, most wood supply projections were performed using a commercial software for forest management modeling (Woodstock^{TM}/Stanley^{TM} package from REMSOFT). Despite the fact that Woodstock models are designed for large-scale problems and that CBM-CFS3 is designed to represent landscape-level forest dynamics, Hennigar et al. (2008) applied their model to a hypothetical and small forest, and studied three initial forest age-structures (young, even-aged and old).Notice that the models developed in the other three initiatives reviewed in Table 1 were also applied on relatively small forest areas. Thus, it is difficult to assess how relevant are their conclusions from a strategic management perspective. Another reason is that these authors assumed that the volume projection used in the timber supply model were static over time. Under this assumptions, tree growth and survival could not be affected by factors such as climate change, insect disturbance, or soil productivity from intensive management. This limitation may be attributed to the fact that, these studies relied on modeling frameworks built on forest inventory data to quantify the relationship between age and carbon stocks. Inventory data may not provide the best insight into relationships between age and ecosystem carbon stocks. As illustrated by States and Bradford (2011), "For example, if a larger proportion of high productivity stands are managed with shorter rotations, then younger aged inventory plots will have a disproportionately high bias toward these productive conditions and older inventory plots will be skewed toward less productive conditions, potentially biasing age-related patterns inferred from these data." In reality, this limitation applies to most previous studies (States and Bradford, 2011). Thus, knowing that more than half the carbon in the forest is not stored in the live trees (Malmsheimer et al. 2011), then it becomes important to improve the estimates of carbon stocks in the other forest pools.

The authors see a major problem with how the different models are combined and used to manage forest activities. In fact, the carbon model is used to account for carbon if a given solution (consisting in a set of management decisions) is applied. The results are then used in an objective function in order to evaluate how optimal is this solution (or set of management decisions). Then, the optimization process is based essentially on the scanning and replacement of the decisions through exhaustive search of the design space. This is a passive way of using the carbon model because it does not enable pragmatic activities of identifying reduction potentials, evaluating measures and supporting implementation each time a management decision should be made. Ideally, such pragmatic activities should be part of the management decision-making process (Schaltegger and Csutora 2012). The idea here is to be able to guide the search process when making a move from one solution to another. We believe that the optimization problem could be solved much better if the carbon impact of every candidate decision about the process of forest growth and harvesting is assessed and evaluated before the decision is made. Thus, the carbon dynamics should be integrated in the modelling of wood supply. As such, available standalone software components for carbon accounting (such as CBM-CFS3) and for wood supply (such as Woodstock) cannot alone provide the level of integration needed.

In this study, the following two questions are explored: (1) How much carbon can be stored in the forest, including the carbon in soil?, and (2) Which forest management regimes best achieve the dual objectives of high sustained timber yield and high carbon storage, including the carbon stored in soil? To answer these two questions, we need a model that can provide reliable predictions of carbon sequestration potential within a given managed forest.

Thus, the specific objectives of this paper were to (i) produce an indicator of carbon sequestration in the forest that can be used to properly incorporate the carbon-dimension into our wood supply model; (ii) demonstrate a new modeling framework that integrates methods and algorithms from the CBM-CFS3 model directly into the wood supply model, and uses them to predict changes in carbon stocks, transfers between pools, and greenhouse gas emissions that would result from every single forest management activity that would result in a change in the forest inventory at the stand level; and (iii) apply this model on a large area of public forest in the province of Quebec, Canada, to determine the maximum carbon volume that can be stored in the forest, and the maximum AAC within the defined forest area if carbon sequestration should be maximized. The models and results of the Chief Forester for the province of Quebec will be taken as our basic scenario. The latter is, among other things, responsible of determining the AAC for Quebec's public forests, and to draw up five-year reviews of the state of the public forest regarding the sustainable forest management.

Materials and Methods

Description of the forest and the management activities

The data used in this research was supplied from the Chief Forester for the province of Quebec (Canada), and was pertaining to an actual Forest Management Unit (FMU 073-51) located in the Outaouais region in western Quebec, which covers 485 000 ha and contains 157 000 stands of even-aged and uneven-aged softwood and hardwood. This region is entirely located in the northern temperate bioclimatic zone and is characterized by its mixed-wood stands (see Figure 1). Dominant canopy species included FSPL group (fir**,** spruce, jack pine and larch), 24 %; cedar, 4%; hemlock, 2%; white and red pine, 6%; poplar, 13%; white birch, 7%; yellow birch, 8%; maple, 28%; and other hardwoods, 10%. Some of the hardwood species (white birch, red maple, poplar) are classified as shade-intolerant hardwood, and others (sugar maple, oak, ash, beech, basswood, Ironwood) are classified as shade-tolerant hardwood.

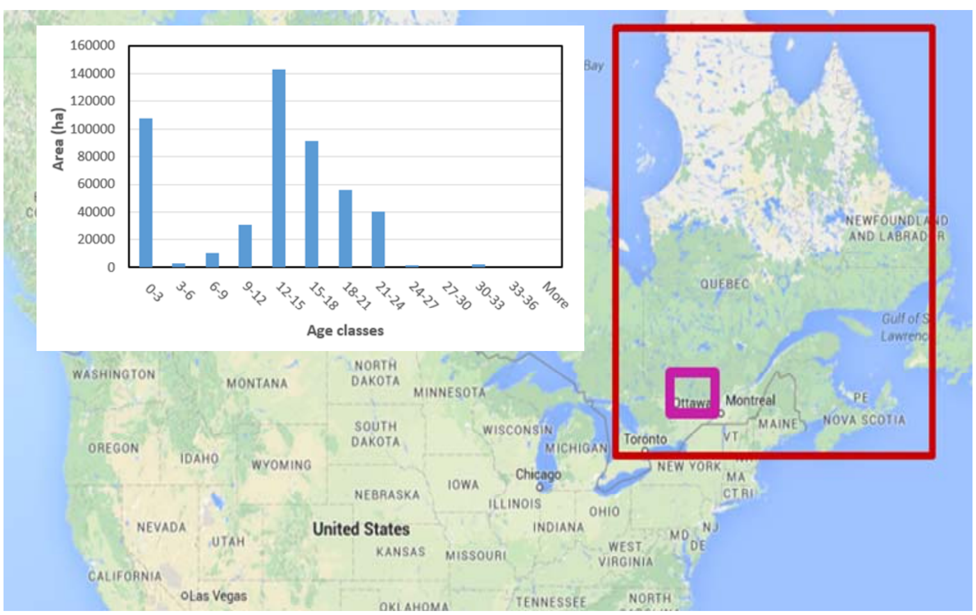

Figure 1. Location of the study area. Initial age class distribution of FMU 071-53 is provided in the inset (top left).

Our objective here was to be in line with the operating practices in the forest industry in the province of Quebec. In FMU 073-71, even-aged and uneven-aged management strategies were applied. The stand treatment interventions applied included planting, commercial thinning, partial cut, and clear-cut with 1, 3, 6 and 9 different variants, respectively. Planting is used to ensure the reconstitution of the forest cover when regeneration is deficient in quantity or quality as a result of natural or human disturbance. Commercial thinning are education processes that involve harvesting a part of merchantable volume in immature stands, and are applied 15 to 30 years before a clear-cut or partial-cut. Partial-cuts are applied to remove 25 to 35% of the merchantable basal area every 20 to 25 years. Finally, when clear-cut treatments are applied, between 90 and 99% of the merchantable volume is removed. Groups of trees and scattered trees can be kept up to allow biological heritage over some parts of the harvested area.

Performance Indicator

The two questions explored in this paper concern the carbon sequestered in the forest during the planning horizon. Large stocks may build-up in above- and belowground biomass and DOM, including soils. In reporting the amount of carbon that has been sequestered, several accounting methods and their variations have been used or proposed in the literature, including the annual average carbon, the annualized carbon, and ton-year carbon. The annual average carbon, the most widely used accounting method, is the sum of total carbon sequestered over a fixed period of time divided by the length of the period (Feng, 2005). On the other hand, the ton-year accounting system, proposed as a solution to the problem of impermanence in forest carbon projects, measures the number of tons of carbon held out of the atmosphere for a given number of years and some quantity of ton-years would be equated with a permanent ton (Marland et al., 2001). These indicators however are not very informative when it comes to evaluate the influence of silvicultural treatments upon the sequestered carbon. The challenge resides in the fact that carbon decays slowly and the effect of a treatment may persist for centuries, thus largely exceeding the planning horizon. We introduce here the *carbon-ton-year* (CTY) as a carbon sequestration unit that accounts for both the amount of carbon stocked and the time during which it is stocked.

A CTY is a unit equivalent to sequestering one ton of carbon during one year. Therefore, 100 tons of carbon sequestered during one year has a value of 100 CTY, and one ton of carbon stocked for 100 years has also a CTY value of 100. Using the CTY, it is possible to sum up all the sequestration in any or all pools resulting from a forest management decision, even if the decomposition far exceeds the planning horizon. Two treatments may have the same CTY value even if, practically speaking, one of those treatments may sequester less carbon but for a longer period of time.

Figure 2 illustrate the calculation procedure of the CTY. The idea consists in using the periodic calculation of the wood supply projections (which take into consideration management activities) to interpolate the yearly carbon increments (see Figure 2, Steps 1 and 2), then to allocated these increments to the appropriate living biomass and DMO carbon pools, and to conduct the carbon transfers between the different pools as a result of biomass turnover and/or carbon decay (see Figure 2, Steps 3, 4 and 5). The CTY value for a given year can be obtained by summing the carbon accumulated in all the pools during this year (Figure 2, Step 6).

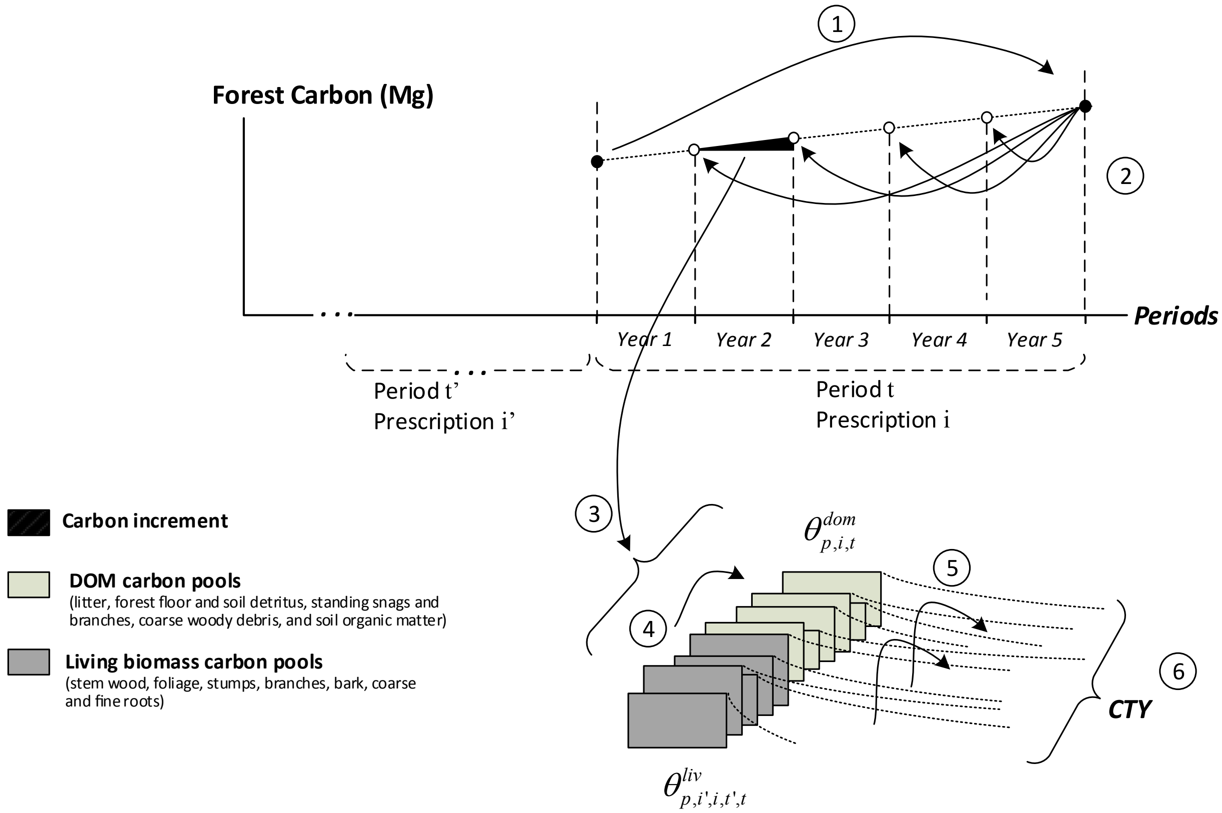

Figure 2. Carbon-Ton-Year (CTY) calculation procedure. (1) Simulate natural forest growth, forest management activities (harvest; clear-cut; …) to determine carbon stocks at the beginning and at the end of current period; (2) interpolate to estimate the yearly carbon increments; then, for each year, (3) allocate the carbon increment to the appropriate living biomass and DOM carbon pools; (4) transfer carbon between pools as a result of biomass turnover (resulting from litter-fall transfer from living biomass to DOM); (5) transfer carbon between pools as a result decomposition factors; (6) sum all components to obtain the CTY.

This procedure appears a priori simple and straightforward. It requires however that the carbon dynamics be integrated in the wood supply projections generation model. As we discussed it earlier, this is not possible using existing software for wood supply projections generation and for accounting for carbon sequestration. In the next sections, we first develop a model for strategic forest management and we demonstrate how we integrate the modelling of carbon sequestration in this strategic model in order to calculate the CTY. Then, we show how the objective function and constraints employed in this integrated model can be adapted to generate models appropriate to the particular questions explored in this paper. A decision support system (DSS), referred to herein *Sivilab* (Siviculture Laboratory), was developed to makes it possible to run these models and produce different optimal forest management plans.

Strategic forest management model

The strategic forest management (SFM) model presented here was developed using the descriptions of the models used by the Chief Forester who is responsible of determining the annual allowable cut in the different forest management units in Québec in accordance with a set of criteria regarding land use and forest management principles. The proposed model is based on a Model-III type formulation (Garcia *et* al. 1990, Boychuck and Martell 1996).

In a Model III, decision variables describe the areas where defined harvesting practices are planned at a specific period of time of the planning horizon; in each period, stands are either harvested, reverting to a specified age class, or not harvested and become one age class older. Sustainability is achieved through a set of constraints enforcing a non-declining even-flow of wood for each species group (Buongiorno and Gilless 2003). Furthermore, the planning horizon is divided into two parts. In the first part, covering the first 30 years, a steady-state constraint ensures an even harvest level from one planning period to the other (typically 5-year periods). On the second part, the harvest level is allowed to increase compared to what was planned for the previous period. The model shown below extends the basic Model-III formulation in many ways, including multiple regional divisions as well as alternative treatments. For model compactness purposes, a single set of variables is used to model the transitions between two treatments. The model objective is to maximize timber supply over the planning horizon using the following equations:

Let

C	Set of all cover types
A	Set of all age classes
I	Set of all treatments
K	Set of regions (landscape is divided in a certain number of regions)
I^k	Set of treatments allowed on region k ($k \in K$)
H	Set of species group for which volume is to be harvested
S	Set of habitat types to be preserved
T^E	Set of planning periods for which the steady states flow constraints are applied
T^N	Set of planning periods for which the non-declining even-flow constraints are applied
$t \in T$	Set of all planning periods ($T^E \cup T^N = T;\ \ T^E \cap T^N = \varnothing$)

Parameters

x_{ack}	Initial area of cover type c and age class a in region k
$\alpha_h^{\min}, \alpha_h^{\max}$	Allowed percentile (negative, positive) deviation on harvested volume of wood type h during the even part of the planning horizon
$\delta_{i',\mathrm{i,k}}$	Minimum number of planning periods before prescription i can be used on region k when i' was the last treatment applied
ϕ_t	Budget allowed for silvicultural treatments in period t
v_{hackit}	Amount of wood type h harvested in period t of region k from applying prescription i on stands of age class a and cover type c
w_{ackst}	Contribution of area with cover type c and age class a in region k to maintain habitat type s in period t
c_{ikt}	Cost per hectare of using prescription i in region k during period t
$r_{st}^{\min}$	Minimum level to preserve for habitat type s in period t
$r_{kst}^{\min}$	Minimum level to preserve for cover habitat s in region k in period t

Variables

X_{ackit}	Area of land from cover type *c* and age class *a* in region *k* to be treated with prescription *i* in time period *t*
G_{ackt}	Area of land from cover type *c* and age class *a* in region *k* left to grow after being treated in time period *t*
U_{ackt}	Area of land from cover type *c* and age class *a* in region *k* left to grow untreated in time period *t*
V_{ht}	Amount of wood of type *h* harvested in period *t*
V_h	Amount of wood type *h* harvested in the steady-states part of the planning horizon

Objective function:

$$Max \sum_{t \in T} \sum_{h \in H} V_{ht} \tag{1}$$

Subject to

$$\sum_{i \in I^k} X_{acik1} + U_{ack1} = x_{ack} \qquad \forall a \in A, c \in C, k \in K \tag{2}$$

$$\sum_{i \in I^q} X_{acikt} = G_{1ctk} \qquad \forall a \in A, c \in C, k \in K, t \in T \tag{3}$$

$$U_{a-1,c,k,t-1} + G_{a-1,c,k,t-1} = \sum_{i \in I^k} X_{acikt} + U_{a,c,k,t} \qquad a \in A, c \in C, k \in K, t \in T \tag{4}$$

$$\sum_{a \in A} \sum_{c \in C} \sum_{k \in K} \sum_{i \in I} v_{hackit} X_{ackit} = V_{ht} \qquad \forall h \in H, t \in T \tag{5}$$

$$V_{ht} \geq \left(1 - \alpha_h^{\min}\right) V_h \qquad \forall h \in H, t \in T^E \tag{6}$$

$$V_{ht} \leq \left(1 + \alpha_h^{\max}\right) V_h \qquad \forall h \in H, t \in T^E \tag{7}$$

$$V_{ht} \geq V_{h(t-1)} \qquad \forall h \in H, t \in T^N \tag{8}$$

$$\sum_{a \in A} \sum_{c \in C} \sum_{k \in K} w_{ackst} \left(U_{ackt} + G_{ackt}\right) \geq r_{st}^{\min} \qquad \forall s \in S, t \in T \tag{9}$$

$$\sum_{a \in A} \sum_{c \in C} w_{ackst} \left(U_{ackt} + G_{ackt}\right) \geq r_{kst}^{\min} \qquad \forall k \in K, s \in S, t \in T \tag{10}$$

$$\sum_{a \in A} \sum_{i \in I} \sum_{c \in C} \sum_{k \in K} c_{aickt} X_{aickt} \leq \phi_t \qquad \forall t \in T \tag{11}$$

The land availability constraints (2) accounts for the initial state of the forests for each cover type c and each age class *a* in every region *k*. It ensures that all the area under management is either assigned to a prescription or left to grow. Constraints (3) ensures that area treated with prescriptions during a given period transition to the corresponding age class, then are left to grow. Constraints (4) ensures consistency in area between each period by stating that area left to grow in period (*t-1*) is either threated or left to grown in period *t*. Constraints (5) allows the accounting of harvest levels for each wood type in each period. The timber flow constraints (6)-(8) are related to the conservation of sustainable yields from forests. Constraints (6) and (7) enforce maximum negative and positive deviation from the even harvest level for each wood type. They are used for the first part of the planning horizon. Constraints (8) makes sure the harvest levels does not decline during two consecutive periods. The area control constraints (9)-(10) are required for the preservation of certain aspects of the forest such as the provision of wildlife habitat or the regeneration of the forest. Constraints (9) represent limits that need to be enforced across the whole area under planning, while (10) represents cover constraints which need to be enforced for each region *k*. In practice, there may be considerable restrictions of this kind and this (along with the number of regions *k*) makes the problem bigger and more difficult to solve. Constraints (11) enforce a budget limitation on the total amount of silvicultural treatments (mostly plantation and thinning) that can be performed in a planning period. A wide range of strategic limitations can be modeled through combinations of constraints (9), (10), and (11), such as minimal or maximal levels for each treatment type, the retention of a given Age-Class distribution, maintaining the historical species groups composition and permit intensive forest management in a given part of the FMU.

Strategic forest management model with strategies to sequester carbon

The model proposed in the previous section needs to be extended to integrate carbon accounting of both living biomass and dead organic matter (DOM). This was done by computing a CTY value for each decision variable in the SFM. In order to do so, we need to know the carbon stocked in the living biomass and DOM pools (see explanation provided in Figure 2). Thus, for each stand modeled in the SFM model, the carbon stock was divided in two set of pools: the carbon sequestrated in living biomass and the carbon in DOM pools. At the time a forest management decision is made, the carbon sequestered in the living biomass has an uncertain future, as it depends on future treatments, but the future of carbon sequestered in DOM pools is fully determined. The carbon in DOM pools will thus transfer from pool to pool according to decay rates taken from CBM-CFS3 until all the carbon reaches the final pool (the atmosphere).

Computing the carbon stocked in living biomass is more straightforward, as it can be inferred from the yield tables described in Boudewyn et al. (2007). However, computing the carbon stocked in DOM pools required us to integrate the equations and matrices composing CBM-CFS3 into the proposed SFM model. The following sets and parameters need to be defined:

P	Set of all carbon pools in the CBM-CFS3 model
P^{dom}, P^{liv}	Set of carbon pools from the DOM and living biomass, respectively
θ^{dom}_{paic}	Number of CTY sequestered in DOM pool $p \in P^{dom}$ resulting from applying prescription *i* in one hectare of forest of cover type *c* from age class *a* in a given planning period

$\theta_{pac}^{liv}, \theta_{pac}^{dom}$ Number of CTY sequestered in pool $p \in P^{liv}$ and $p \in P^{dom}$ respectively, resulting from growing one hectare of forest of cover type *c* from age class *a* in a given planning period to age class *(a+1)* in the following period

Furthermore, we define Q_{pt} as the accounting variable that corresponds to the Total amount of carbon sequestrated in pool *p* during period *t* (measured in CTY). The following constraint can thus be added to the SFM model to allow the computation of carbon sequestration. Accounting of carbon stored in living biomass is made solely using variables related to forest growth, while DOM pools are affected by both silvicultural treatments as well as forest growth.

$$\sum_{a \in A} \sum_{c \in C} \sum_{k \in K} \theta_{pac}^{liv} \left(U_{ackt} + G_{ackt} \right) = Q_{pt} \qquad \forall p \in P^{liv}, t \in T \tag{12}$$

$$\sum_{a \in A} \sum_{c \in C} \sum_{i \in I} \sum_{k \in K} \theta_{paci}^{dom} X_{ackit} + \sum_{a \in A} \sum_{c \in C} \sum_{k \in K} \theta_{pac}^{dom} \left(U_{ackt} + G_{ackt} \right) = Q_{pt} \qquad \forall p \in P^{dom}, t \in T \tag{13}$$

Two models can now be proposed in order to account for carbon maximization strategies. The first model aims at maximizing carbon sequestration (measured in CTY). This model is labeled as SFM-C model and has the following structure:

$$Max \sum_{p \in P} \sum_{t \in T} Q_{pt} \tag{14}$$

Subject to constraints (2), (3), (4), (5), (9), (10), (11), (12) and (13).

Notice that model SFM-C may become equivalent to the CBM-CFS3 model if it is forced to apply no treatment for the whole area under management thus simulating natural forest growth. This amounts to changing the SFM-C model by adding the following constraint:

$$\sum_{a \in A} \sum_{c \in C} \sum_{i \in I^k} \sum_{k \in K} \sum_{t \in T} X_{acikt} = 0 \tag{15}$$

We therefore refer to this model as SFM-N. This model was used to determine how much carbon can be stored in the forest without further human intervention. This issue is the subject of the first question explored in the paper.

While interesting, the SFM-C model is of limited practical value considering that forests serve multiple purposes, including harvesting of wood. Therefore, a compromise between yield and carbon sequestration was explored. To do this, we defined V_{lt}^{0} as the value obtained for harvest type *h* from the optimal solution to the SFM model, then, we used this parameter to add a set of constraints (16) to ensure a maximum deviation from the optimal harvest level for each wood type. Thus, by varying the value of β between 0 and 1, it is possible to explore the compromise region between yield and carbon sequestration:

$$V_{ht} \geq \left(1 - \beta\right) V_{ht}^{0} \qquad \forall h \in H, t \in T^{E} \tag{16}$$

By subjecting objective function (12) to constraints (2)-(4); (8)-(11); and (14), we defined a new model that we used to maximize carbon sequestration while ensuring a predefined minimum harvest level or volume yield. We labeled this model as SFM-β. This model was used to address the second research question explored in this paper.

Validation scenarios

The models described above were implemented in a DSS called *Silvilab* and developed by FORAC, a research consortium based at Université Laval in Quebec City, Canada. Silvilab is a web application that can be used to visualize, evaluate and compare strategic forest management and industrial development plans of the forest.

The freely available CBM-CFS3 simulation software (Kull et al. 2011) was used to verify and validate the models presented above. We compared the sequestered carbon estimates obtained from Silvilab with the CBM-CF3 simulator estimates assuming natural growth of the forest for a period of 150 years. The CBM-CFS3 model incorporates natural disturbance and land-use change information, and a schedule of forest-management activities. By running CBM-CFS3 to simulate the case where no land-use change information is included and no forest management activity is scheduled, then we obtain a set of data that is used to compare to results obtained from the SFM-N model.

Since, the CBM-CFS3 simulator incorporates data for over 60 tree species found in Canada and in northern areas of the U.S and can track carbon for specific species or for groups of species, three alternative forest models were developed. In the first set of models, we consider each of the 16 species available in the FMU. However, in the second and third sets, these species we grouped by species composition. In the second set, two species groups were used (Softwood (SW), Hardwood (HW)). In the thirst set, the HW group was further divided into two groups (shade tolerant (THW) and shade intolerant (IHW) hardwood).

Results

Models verification and validation

We compared the total amount of carbon sequestered (*Qp*) over time in three broad pools (merchantable volume; foliage; others) as calculated respectively using the CBM-CFS3 simulator and the SFM-N model implemented in Silvilab. We did this for each of the three species groups' scenarios. The match was almost perfect. The two models provided very similar projections of total sequestered carbon in each pool. The resulting average precisions were %99.73, %99.97 and %97.76 for the first, second and third sets, respectively. The slight difference could be related to the fact that the calculations in CBM-CFS3 are done on an annual growth scheme while 5-year time periods are used in Silvilab (30 5-year periods).

On another level, the results obtained from the simulations discussed above were used to analyse the distribution of the stock of carbon between the different pools in the forests including aboveground biomass, belowground biomass, deadwood, litter, and soil organic carbon (Figure 3). It appears that only one-quarter of the carbon stock is estimated to be stored in the aboveground live pool. This again highlights the critical necessity for the inclusion of the different pools, and DOM pools in particular, in carbon accounting analysis of strategic forest management.

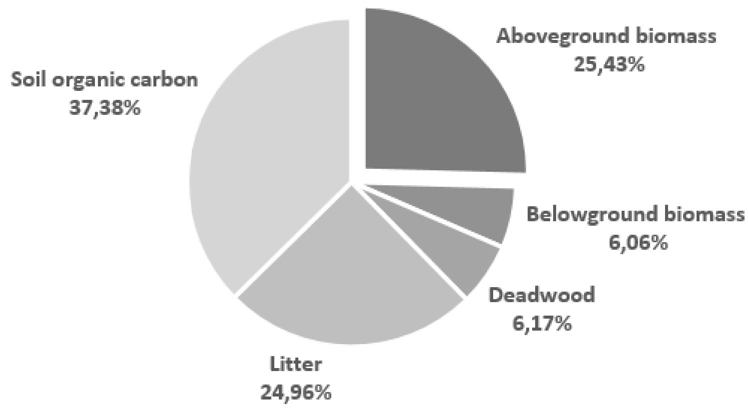

Figure 3. Distribution of Carbon stocks in FMU 073-51 calculated using Silvilab.

Table 2. Forest yield of merchantable volume (in millions of m^3) and carbon sequestered (in billions of CTY) for the 100 years, for nine alternative management objectives for the 073-51 FMU.

Model (objective)	Total harvest		Total sequestration	
	$\sum\sum V_{ht}$ (10^6 m^3)	Portion of RMV (%)*	$\sum Q_p$ (10^9 CTY)	Portion of RMC (%)**
SFM-N (Natural growth)		0.0	20.60	**100.00**
SFM (Maximum volume)	107.74	**100.00**	18.36	89.13
SMF-C (Maximum carbon)	37.54	34.85	20.99	101.89
SFM-β (Maximum carbon constrained)				
β = 0.005	107.12	99.43	18.47	89.78
β = 0.01	106.66	99.00	18.54	89.98
β = 0.02	105.58	98.00	18.62	90.37
β = 0.10	97.97	90.00	19.08	92.61
β = 0.25	80.81	75.00	19.71	95.66
β = 0.50	53.87	50.00	20.43	99.17

* The SFM model is used in the scenario that generates the Reference Maximum Volume (RMV)
** The SFM-N model is used in the scenario that generates the Reference Maximum Carbon (RMC)

Maximizing carbon stocks

As expected, management model SFM-C produced the greatest increase of carbon stocks from the start of the planning horizon to its end (see Figure 4a). Near $21x10^9$ CTY could be sequestrated in the studied forest region. The carbon stocks were 1.89 % higher than would be the case with the SFM-N model, i.e. letting the forest grow naturally with no harvest or other treatment (Table 2). The SFM-C model achieved the high levels of carbon stocks by harvesting almost constant volumes of wood from one period to another (see Figures 4b and 5). Harvesting was conducted in general with partial and clear cutting (Figure 6a and b). Figure 6d shows that some commercial-thinning took place between the 70th and the 105th years of the planning horizon.

These treatments are attributed, among other things, to the budget constraints imposed on silvicultural treatment during these periods of the planning horizon. While the volume was non-declining over the entire planning horizon, an increase in the number of hectares treated using the different stand treatments can be observed during last two periods (or ten years) in the planning horizon (see Figure 6). This informs us that the stands treated during this period were young or, in average, less-productive than the other stand. Thus, larger areas needed to be harvested as a consequence of the non-declining harvest constraints. However, the same cannot be said about carbon sequestration. In fact, the carbon sequestration started to decline during this same period. This can be explained by the fact the stands treated during this period were young. Young stands are known to generally produce less biomass than older stands. The age structure graph shown on Figure suggests the dominance of old trees in the forest region studied. Thus the forest is being converted to younger forest. As stated by Cooper (1983), "the conversion of older forest to younger forests has generally been shown to release carbon to the atmosphere". Notice the plantation and commercial thinning treatment planned for period 30 are unnecessary as their impact of volume or carbon sequestration cannot be accounted for in the objective function. Here also, the allocation of some budget to carry out silvicultural treatment during this period explains the planning of these treatments.

Model SFM simulates the traditional management strategies where volume maximization is the primary objective. This scenario resulted in the largest overall volume (Figure 4b). In the meantime, there is more than 8% less carbon in the forest at the end of the planning horizon. Large forest areas were treated using the partial-cut and clear-cut treatments (Figure 6a, b). Harvesting was conducted using the steady or non-declining even-flow principle, discussed earlier applied using constraints 5 and 6. This principle explains the harvest volume increases that can be observed between periods 14 and 19 for the SFM model simulation. Indeed, the Chief Forester in Quebec applies the non-declining even-flow principle on the studied management unit like any other management unit in Quebec (Bureau du forestier en chef 2013). Thus, on Figure 6, it is possible to notice a change in the overall number of hectares treated, at the end of the first 6 to 7 periods (or the first 30 years). It takes a number of periods before the increase in harvests volume becomes visible, and this number varies from one management model to the mother. However, our analysis shows that the increase in harvests volume varies in time of occurrence and in magnitude from one specie to the other (see Figure 5). For instance, with model SFM-C, the harvests volumes of shade-intolerant hardwood and softwood remained almost unchanged over the planning horizon, however, a significant shift in the harvests volume of shade-tolerant hardwood occurred from period 20 to period 24. Notice that, like with the SFM model, model SFM-C has a non-declining volume yield constraint. However, unlike the SFM model, the objective function of the SFM-C model does not aim at volume maximization. In fact, this situation ensures that the generated plans remain feasible and practical from the perspective of the Chief Forester.

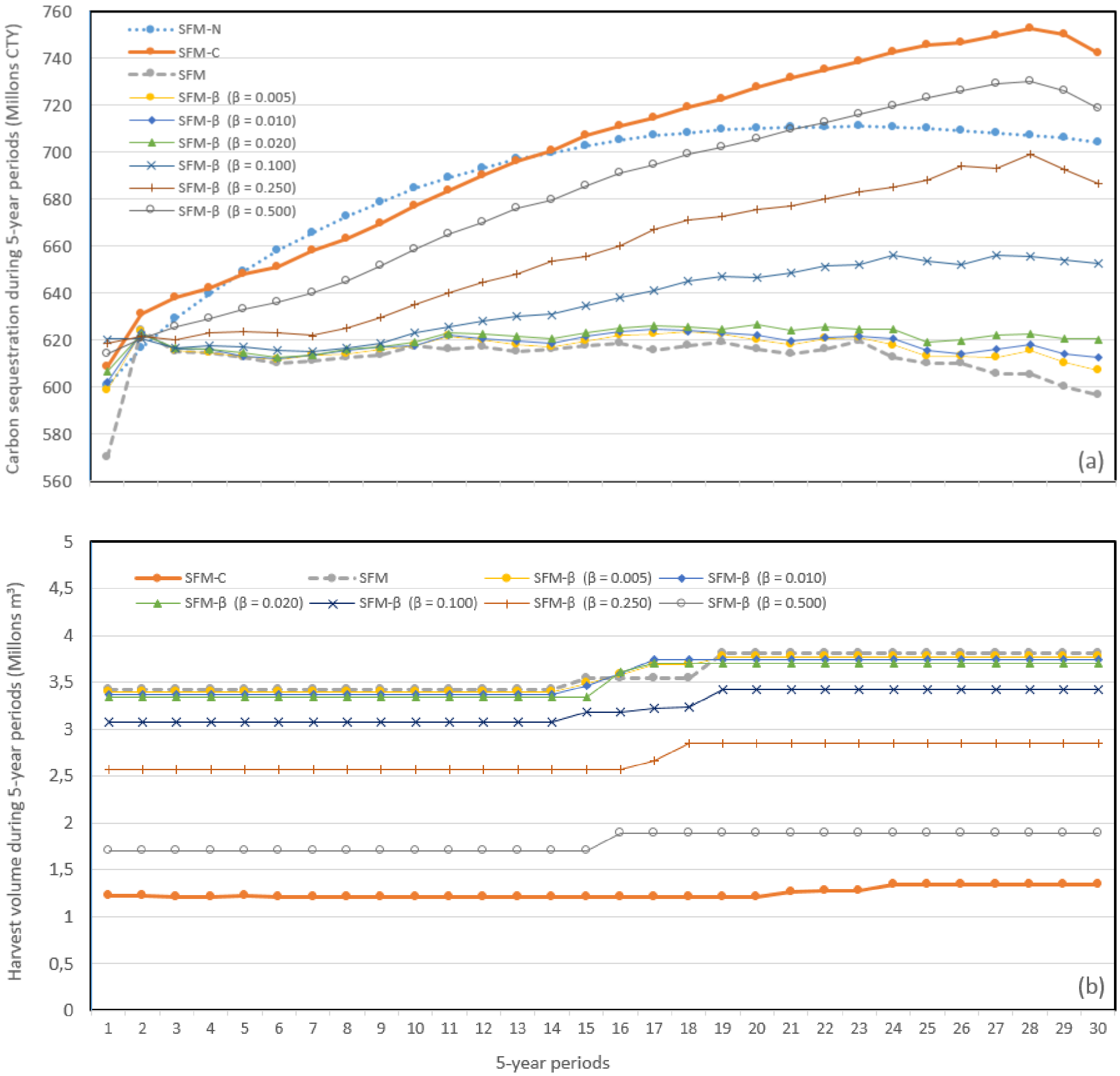

Figure 4. Carbon sequestration (a) and harvest volume (b), for each 5-year period in (Millions m^3) as calculated using nine alternative strategic management models.

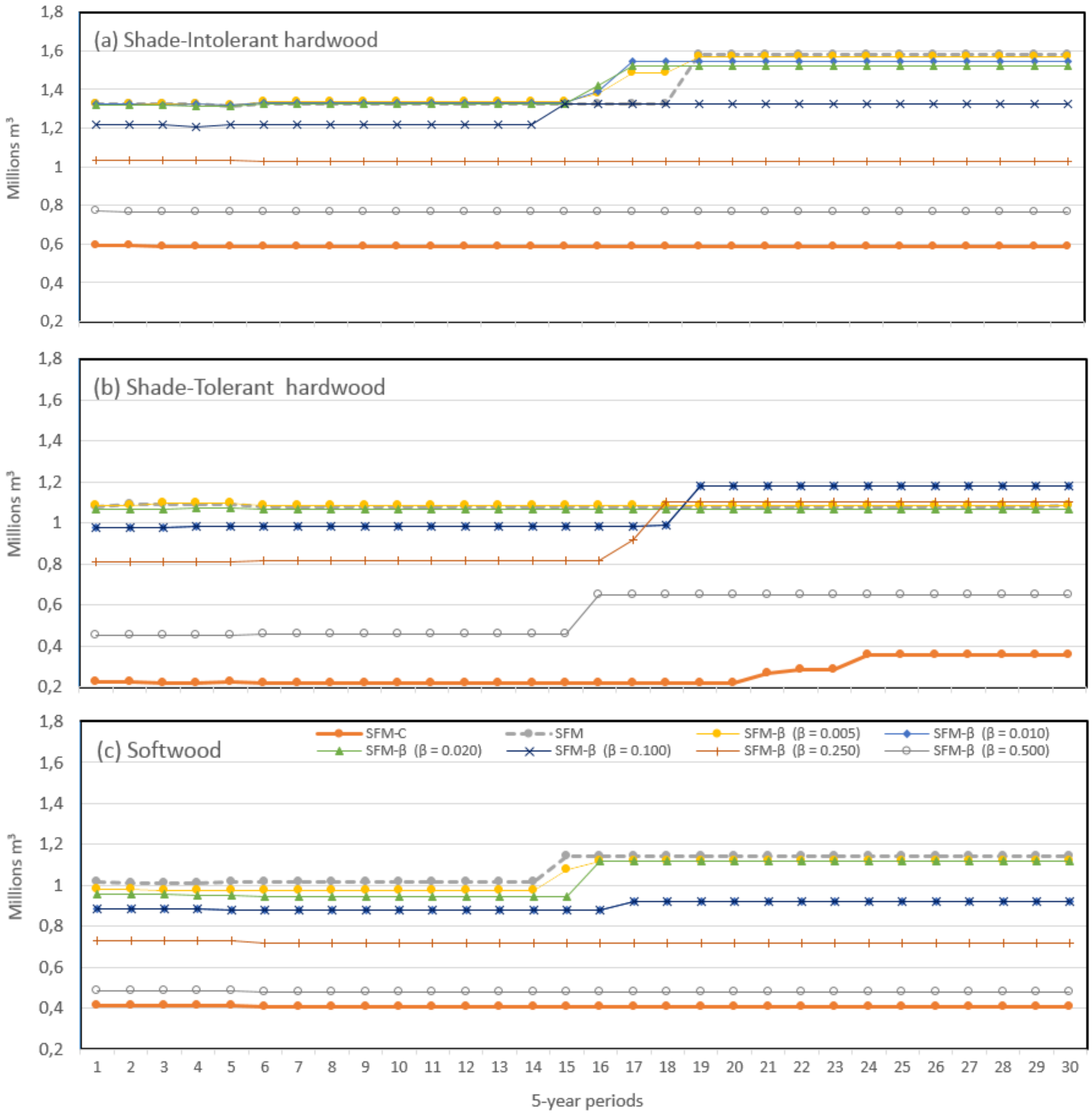

Figure 5. Harvest volume by species groups: (a) Shade-Intolerant, (b) Shade-Tolerant, and (c) Softwood for over the planning horizon as calculated using nine alternative strategic management models.

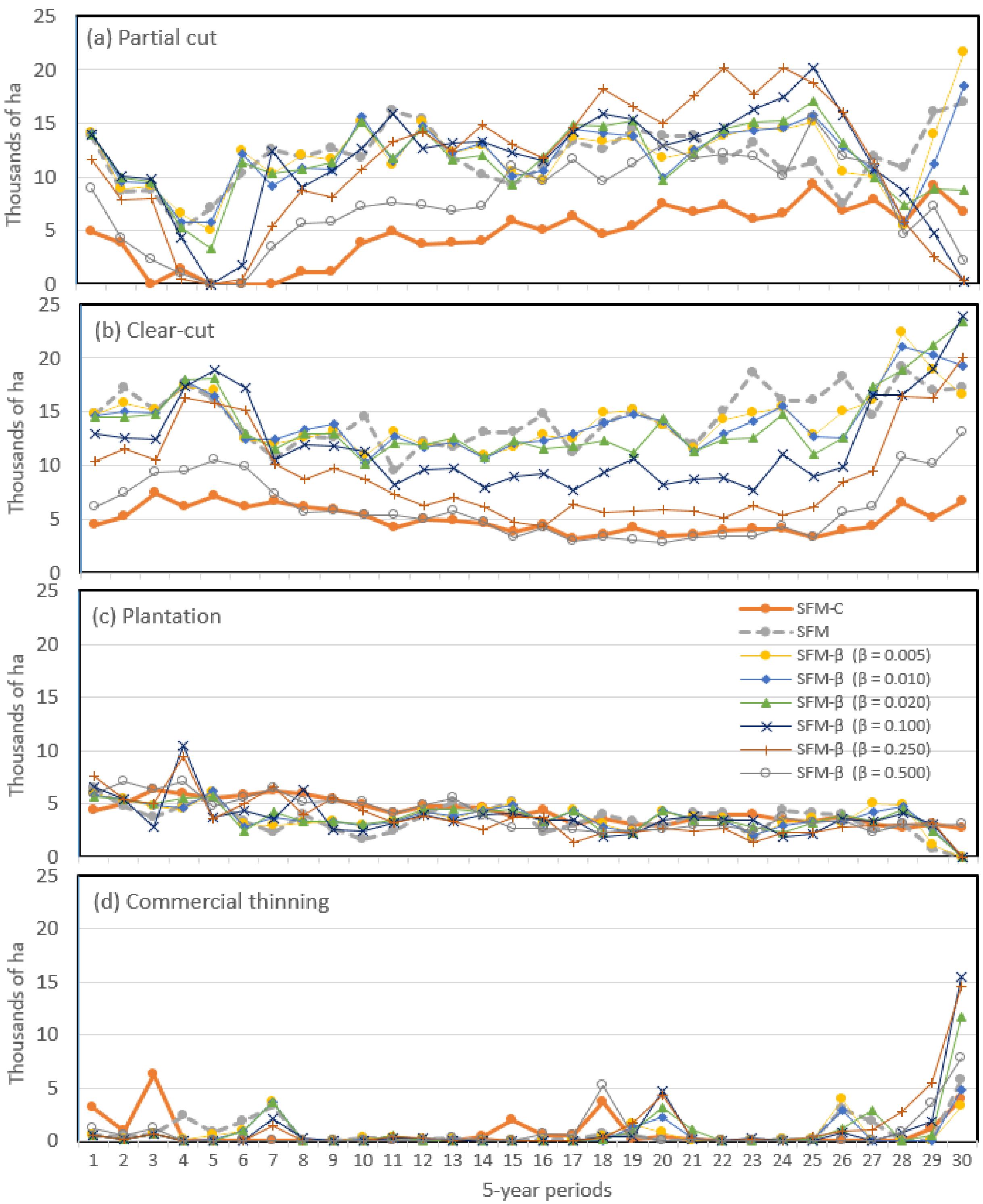

Figure 6. Forest areas for which treatments partial cut (a), clear-cut (b), plantation (c), and commercial thinning (d) were applied over the planning horizon as calculated using nine alternative strategic management models.The results are grouped by family of treatment.

Maximizing carbon stocks with constraint on volume

Six scenarios aimed at achieving the dual objectives of high sustained timber yield and high carbon storage with parameter β set to 0.005, 0.01, 0.02, 0.12, 0.25 and 0.5. As expected, the yield differences between the SFM-β scenarios and the SFM-N scenario correspond almost perfectly to the values given to parameter β (see Table 2 and Figure 7). Figure 4, all six scenarios resulted as expected in higher stocks of carbon but lower harvest volumes than the SFM model. Here too, the harvest volume increases that can be observed between periods 14 and 24 for the different simulations could be attributed to the implementation of the non-declining even-flow principle during the harvest. Figure 5 shows that, the volumes of hardwood harvested are in general higher that the volumes of softwood. This can be explained by the fact that the forest contains high proportions of hardwood. Notice however that, in scenario SFM-C, most of the hardwood harvested is shade-intolerant. This is probably due to the fact that shade-tolerant species can sequester carbon for longer period a time. Finally, Figure 5c shows that plantation was used on a regular on ongoing basis but is slowly decreasing over the planning horizon in the different scenarios. According the chief forester, plantation treatments ensure the reconstitution of forest cover when regeneration is deficient in quantity or quality because of a natural or manmade disturbance.

Discussion

The results presented in this paper are part of our effort to integrate carbon dynamics in the management decision-making process as this is expected to better achieve the dual objectives of high sustained timber yield and high carbon sequestration. Our results go against the commonly held belief is that it is better to keep the forest grow naturally and avoid cutting living trees. If we consider the carbon sequestration resulting from model SFM-N as the highest carbon stock that could be sequestered (and refer to it as the Reference Maximum Carbon or RMC), and the volume resulting from model SFM as the largest volume that could be harvested in the forest (and refer to it as the Reference Maximum Volume or RMV), then we can use the results depicted in Table 2 to analyze the performance of the different scenarios with respect to the RMV and RMC. When maximizing harvest regardless of carbon sequestration (scenario using the SFM model), carbon sequestration represented 89.13% of the RMC. When the SFM model was forced to restrict harvests to 50% of the RMV (this is the scenario with the SFM-β model and β = 0.50), it was possible to achieve 99.17% of the RMC. When carbon was maximized regardless of volume (SFM-C model), the RMC was improved by 1.89% and the expected volume was 34.85% of the RMV. This result clearly demonstrates that recognizing the carbon in above- and belowground biomass and DOM, including soils, does not subsidize the no-harvest scenario or lengthening harvest cycles. This argues in favor of the scenarios about the strategic forest management with strategies to sequester Carbon.

Figure 7 compares the maximum volumes and the maximum carbon sequestration between the simulated models. It shows that increasing carbon stocks in the analyzed forest leads to lower timber supply, and above a certain β value, the increase in carbon sequestration comes against dramatic reductions in volume. To find to 'optimal' β value, it is probably necessary to conducts an economic or cost-effectiveness analysis. The presented simulations showed that the proposed models have a level of details that makes it possible to consider a host of sophisticated scenarios of strategic forest planning. This enabled us to address effectively the two research questions raised in this paper, and paves the way for analysing the economic potential of carbon sequestration in forests considering factors such as the treatments costs, or the timber and carbon markets.

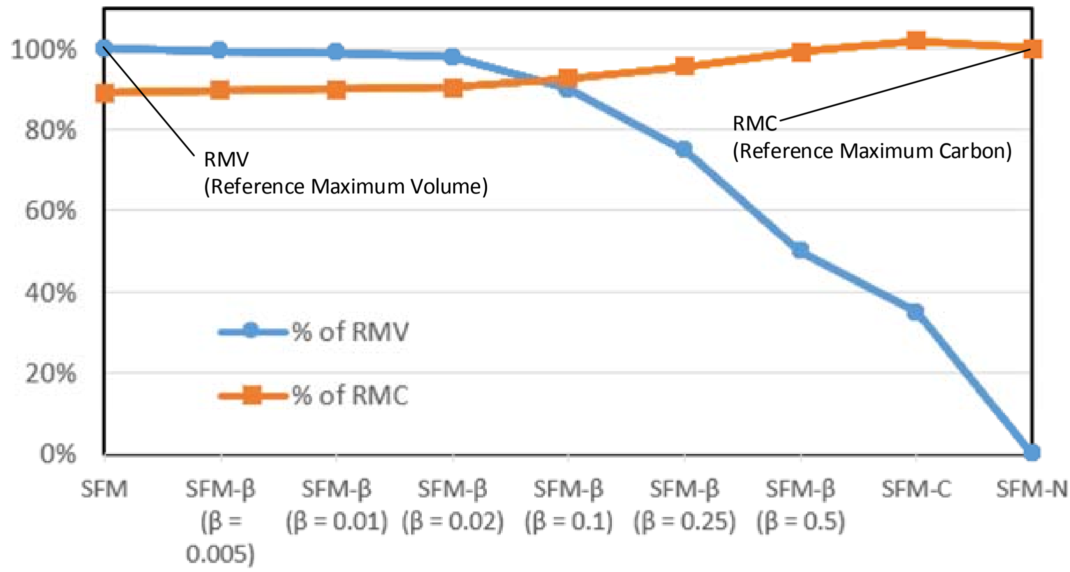

Figure 7. Comparison of the percentage of maximum volumes vs percentage of maximum sequestration for all models.

While it was possible for us to validate model SFM-N against CBM-CFS3, the validity of the other models, which could result in a variety of management scenarios, is difficult to ascertain as it depends on validity of the data and parameters values. In particular, in the calculation of the CTY, we assumed that the carbon sequestered in the DOM pools will transfer from pool to pool according to decay rates until all the carbon reaches the atmosphere. As such, none of the considered planting, commercial thinning, partial cut, and clear-cut stand treatments is expected to release carbon in the atmosphere. However, there could be emissions associated with natural disturbances like fire, insect defoliation and slash burning. It is true that these emissions are accounted for in the CBM-CFS3 model, and this model uses sophisticated algorithms to explicitly simulate individual annual disturbance events. However, if there are significant changes in the cycles of these disturbance events, then there could be substantial discrepancies between the calculated CTY estimates from our management models and the actual figures of carbon sequestration.

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