IMPLICATIONS OF A MARKET FOR CARBON ON TIMBER AND NON-TIMBER VALUES IN AN UNCERTAIN WORLD

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Abstract

Despite considerable interest in the potential for forests to sequester carbon, the impact of carbon management on the provision of timber and non-timber resources has received relatively little attention in the literature. The introduction of value for stored carbon may result in modifications to traditional forest management objectives, generating trade-offs with other forest resources depending on the incentives provided by carbon markets. This paper investigates these issues by examining the impact of a particular form of carbon market on timber and non-timber values in a managed forest. An integrated modeling framework, developed for the incorporation of carbon management into operational timber management modeling tools, is also described.

There is still substantial debate over how to properly credit carbon sequestered in forests. To date, there has been little research on how the form of a carbon market will impact the operations and objectives of forestry firms. Alternative market structures could produce very different responses in terms of rotation age, net present value and harvest policy. Here, a specific form of carbon market, the specified level contract, is investigated. Forestry firms are assumed to reach contracts with carbon-seeking agents which "guarantee" that a specified level of carbon stock will be maintained over a defined time period.

Optimal forest management decisions are examined by implementing an optimization model for a specific land base in Alberta. The Woodstock forest modeling package is used for optimization. Analysis of trade-offs is based on the work of Armstrong *et al*. (1999, 2003) which assess non-timber resources using the natural disturbance approach to forest management. The analysis is then expanded to include a more rigorous, and realistic, depiction of carbon and carbon stock changes. Using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), carbon yield curves are developed which are integrated directly into the Woodstock forest management model. These carbon yields capture dynamics specific to separate biomass and dead organic matter (DOM) carbon pools and are represented for individual forest cover types.

Interestingly, the inclusion of DOM carbon generates unexpected relationships between non-timber resources and incentives to sequester carbon. Results show that the presence of co-benefits will depend upon forest cover type, the harvest flow regulation faced by the managing firm and the incentives for timber supply provided by the market. Furthermore, firms that agree to enter contracts for carbon sequestration appear to do so at the expense of a decline in timber supply, with estimates of the opportunity cost of carbon management falling within the range of those found in recent literature.

Keywords: Carbon Sequestration, Wildlife Habitat, Timber Supply, Co-Benefits, Natural Disturbance Model, Woodstock, CBM-CFS3.

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1.0 Introduction

In recent years there has been considerable interest in climate change, greenhouse gas emissions and the role of forests in the global carbon cycle. By recognizing the potential for forests to sequester carbon, Articles 3.3 and 3.4 of the Kyoto Protocol have helped generate this interest by creating an opportunity for forestry activities to contribute to an individual country's emission reduction targets. However, modifying forest management methods to focus on increasing the volume of stored carbon may result in trade-offs with other forest management objectives. Understanding how carbon sequestration programs will affect both forest management decisions and non-timber forest values is thus a critical component to implementing forest carbon management effectively.

To address these issues, several papers (Creedy and Wurzbacher, 2001; van Kooten *et al.*, 1995; Plantinga and Birdsey, 1994) have addressed the impact of carbon sequestration programs on stand management and optimal forest rotations. Further studies (Krcmar and van Kooten, 2005) have compared the costs of producing carbon credits under varying forest management and post-harvest strategies while others (Plantinga and Wu, 2003; Matthews *et al.*, 2002) have looked at possible co-benefits from carbon sequestration under afforestation programs. These studies have advanced our understanding of the interaction between forests, carbon and markets significantly. However, a number of unresolved issues remain. In this paper two of those issues are examined; the impact of the form of the carbon market on the response from the forestry firm, and the impact of forest carbon management on non-timber resources.

The approach taken is to assess a specific form of contracting for carbon, in which a forestry firm "guarantees" a carbon-seeking agent that it will maintain a specified level of carbon stocks over a defined time period, on a multiple stand forest management enterprise.[1] The impacts of this market for carbon on the firm's management of timber

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[1] While there has been relatively little research on the impact of the form of a carbon market on the operations of firms, several alternative mechanisms have been discussed in the literature. Beyond a

and non-timber resources are then analyzed. Of particular interest, while the costs of producing carbon offsets through forestry activity have been widely investigated (van Kooten *et al.*, 2004; Sohngen and Mendelsohn, 2003), it has also been recognized that a key to making carbon mitigation activities more efficient may be to balance them with other economic, environmental and social goals of land use (Metz *et al.*, 2001). Important co-benefits of forest carbon mitigation may include providing habitat, conserving biodiversity and improving ecosystem productivity.

Yet, despite this recognition, the impact of carbon management on non-timber values has not had substantial attention in the literature (a notable exception is Englin and Callaway, 1995).[2] The impact of carbon markets on non-timber resources could be substantial. Market effects may be felt long before the impacts of climate change are fully realized, and may not allow sufficient time for adaptation by the plant and animal species that are often associated with non-timber values. Moreover, for Parties to the Kyoto Protocol, the rules related to implementing forest carbon management activities under Article 3.4 require that they contribute to the conservation of biodiversity and the sustainable use of natural resources (UNFCCC, 2002).

These issues of carbon market structure and its impact on timber and non-timber resources are examined by implementing an optimization model for a specific land base in Alberta. Given an initial age-class distribution for the region of interest, an optimal harvest model is developed. This model is based on prices for timber only and includes an even flow timber yield constraint. Carbon dynamics are incorporated using the Carbon Budget Model of the Canadian Forest Sector (Canadian Forest Service, 2005), which allows the model to capture stocks and fluxes between biomass and dead organic matter (DOM) carbon pools. Carbon values are introduced in the contract system described above, and the model is augmented to include carbon level constraints. Analysis of non-timber resources is carried out using the natural disturbance approach to forest management, and follows the techniques developed by Armstrong (1999) and Armstrong *et al.* (1999, 2003). This approach allows the comparison of timber

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specified level contract, firms could be rewarded or penalized for accumulations and removals of carbon via a credit/debit system, or a policy framework involving carbon taxes and subsidies could be used.

[2] There has, however, been considerable analysis done of the impact of climate change on non-timber values (Sohngen *et al.*, 1999; Binkley and van Kooten, 1994).

harvesting outcomes with timber alone as the price incentive, and with timber and carbon price incentives, with what would have existed "naturally".[3] Results from this case study provide insight into the expected response of forestry firms to the development of carbon markets, forestry firms' willingness to accept for carbon and the relationship between non-timber resources and carbon sequestration programs.

2.0 Input Data

2.1 Forest Structure

The inventory and yield relationships used in this study are based on data provided by Daishowa-Marubeni International Ltd. (DMI) for part of their Forest Management Agreement Area in North-Central Alberta, Canada. The area is an important timber producing area for a pulp mill and several sawmills. The study area is approximately bounded by 56°N and 57°40′N latitude and 115°W and 117°W longitude. The starting age-class distribution is shown in Figure 1. This inventory represents the current condition of the 888 713 ha of net merchantable land base for the study area. The net merchantable land base is part of the total forest area considered available for timber harvest activities. The area is net of stands which are considered never merchantable due to low projected volume, muskegs and other wetlands, areas deleted for stream and lake buffers and other operational considerations. Harvestable volumes are assumed to change with stand age according to the yield tables presented in Figure 2. These yield tables show declining volumes somewhere between 100 and 150 years of age. These declines reflect stand break-up.

The most striking feature of the starting inventory presented in Figure 1 is the large area of forest in the 60 year age class (324 243 ha or 36.5% of the land base). This spike in the age-class distribution is characteristic of forests subject to the lognormal disturbance regime characterized by Armstrong (1999). It may also play a significant role in the carbon dynamics of the forest resulting from subsequent management activities (Kurz *et al.*, 2002).

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[3] This paper is an extension of the work done in this regard by Armstrong *et al.* (1999). The main improvement involves the use of the CBM-CFS3 to model separate biomass and DOM carbon pools, allowing for a more realistic representation of overall forest carbon dynamics.

Figure 1: Initial Age-Class Distribution for the Study Area.

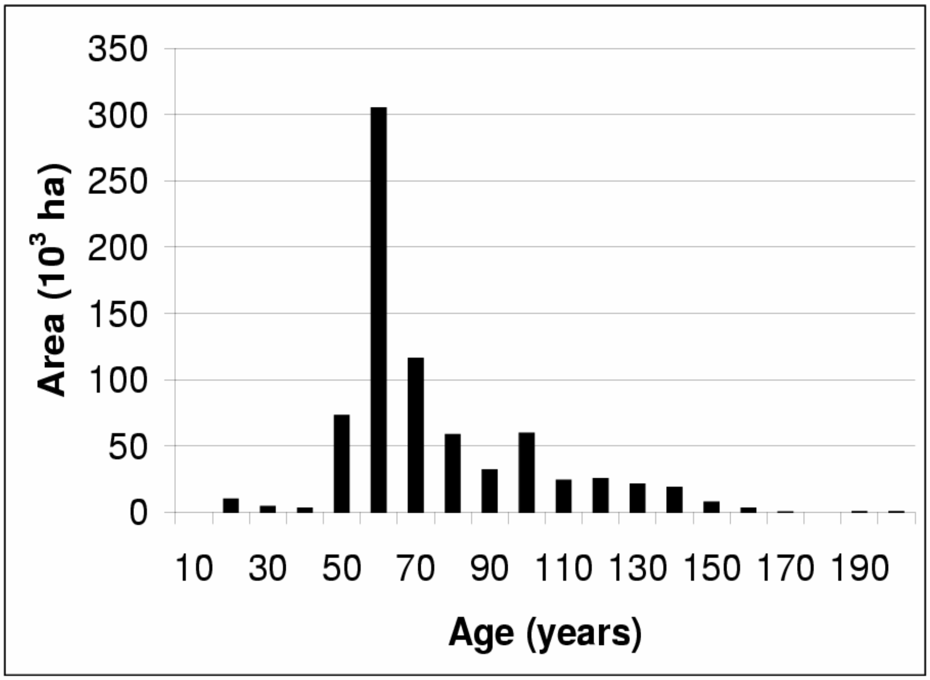

Figure 2a: Softwood Merchantable Volume Yields.

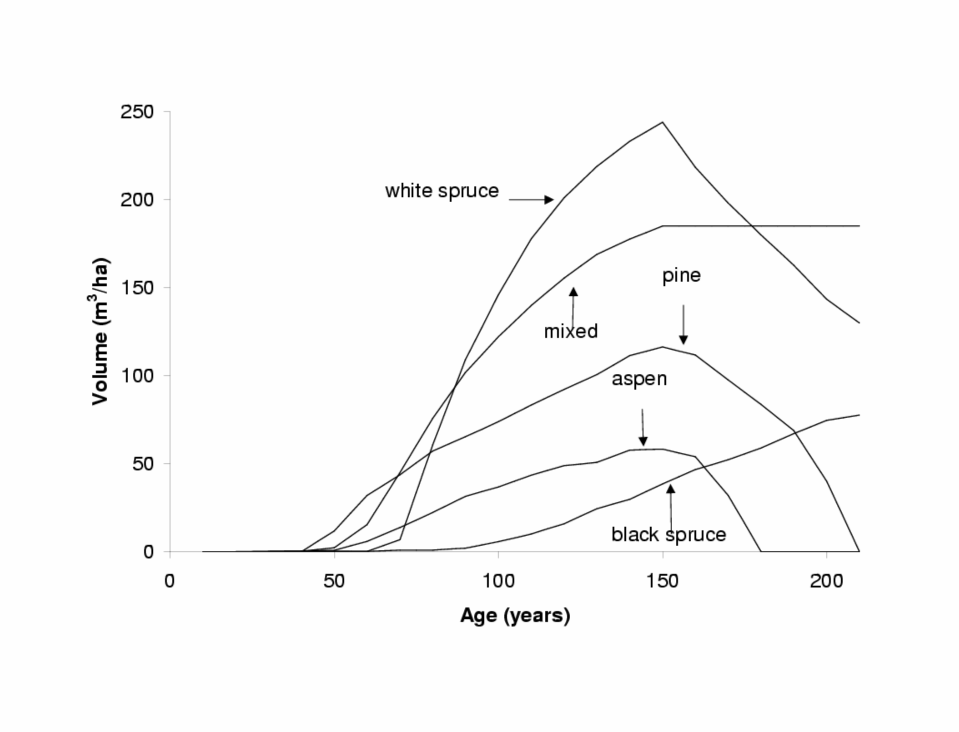

Figure 2b: Hardwood Merchantable Volume Yields.

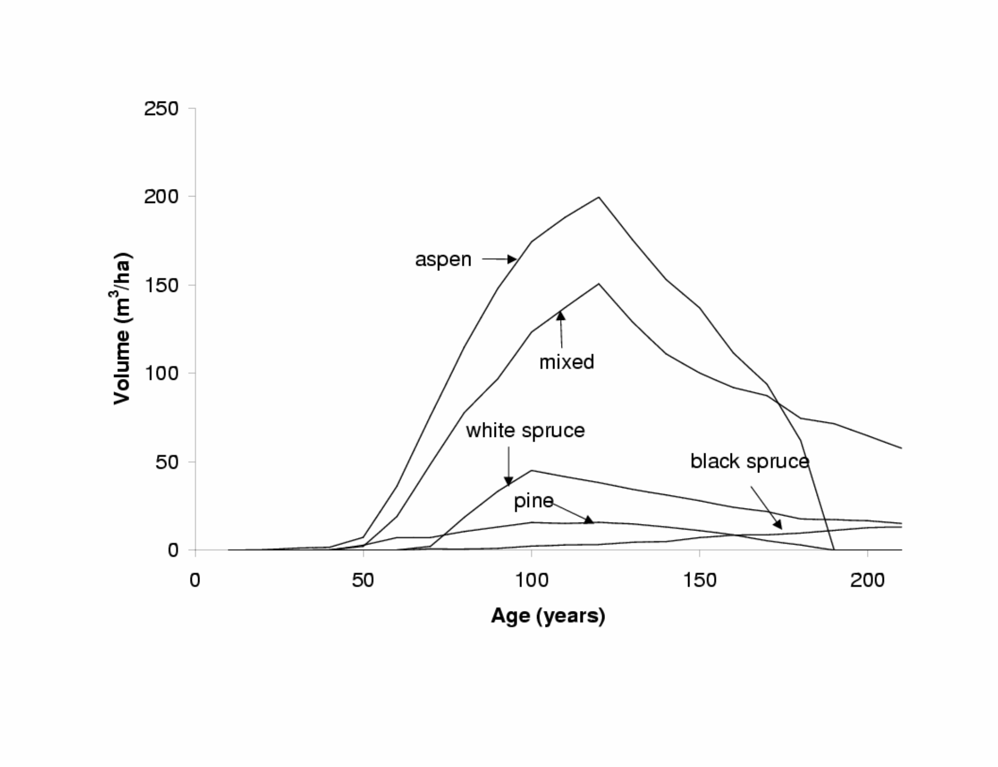

Figure 2(a & b): Merchantable Volume Yields (m^3/ha) by Cover Type and Age (yr).

2.2 Habitat Quality

The representation of habitat quality developed by Cumming *et al.* (1994) is used here. They describe a forest in terms of area in cover type by habitat stage combinations. The cover types were based on species composition of stands. The recognized cover types were pine, white spruce, aspen, mixed and black spruce. The white spruce, aspen and mixed cover types represent stands that occur on mesic sites. Six habitat stages were recognized: establishment, the interval to maximum stem density, the interval to maximum crown closure, the interval to maximum basal area, a mature stage and an overmature stage. These habitat stages were related to stand age and cover type as shown in Table 1.

Table 1: Habitat Stage Definition by Forest Cover Type and Age Range. After Cumming et al. *(1994).*

Habitat Stage		Age Range (Years)	
ID	**Description**	**Aspen Cover Type**	**Other Cover Types**
1	Establishment	0 – 5	0 – 5
2	To Maximum Stem Density	6 – 15	6 – 25
3	To Maximum Crown Closure	16 – 30	26 - 60
4	To Maximum Basal Area	31 – 60	61 – 100
5	Maturity	61 – 80	101 – 150
6	Overmaturity	81+	151+

Cumming *et al*. (1994) relate cover type and habitat stage to habitat quality for five vertebrate species: American marten (*Martes americana* Turton), meadow vole (*Microtus pennsylvanicus* Ord), broad-winged hawk (*Buteo platypterus* Vieillot), black-throated green warbler (*Dendroica virens* Gmelin), and northern three-toed woodpecker (*Picoides tridactylus* Linnaeus). These species were selected because they have very different habitat requirements, allowing for a convenient shorthand representation of the structure of the forest. They also have relatively small home ranges, which allows for their habitat requirements to be represented in an aspatial model (Armstrong *et al*., 2003).

Cumming *et al.* (1994) justify their choice of species as follows:

> The pine (sic) marten was chosen for its preference for mature stands containing white spruce, and because it and other large mustelids face habitat losses throughout the circumpolar boreal forests… . The meadow vole illustrates a species dependent upon open, recently disturbed habitat. The three-toed woodpecker is characteristic of old coniferous stands, whereas the black-throated green warbler is associated with mature and older mixed and coniferous stands. The broad-winged hawk nests and forages almost exclusively in mature deciduous stands.

The habitat quality indices developed by Cumming *et al.* (1994), and presented in Table 2, were based largely on a literature review. Habitat quality index is coded as an integer between one and six inclusive, where one represents unsuitable habitat and six represents ideal habitat. This numeric scale follows that used by McNichol *et al.* (1981) to indicate avian abundance in different habitats. It proves to be convenient for the modeling presented here.

Table 2: Habitat Quality Index by Species, Cover Type, and Habitat Stage. Blank Entries Represent a Habitat Quality Index of 1. Reproduced from Cumming et al. *(1994), Table 3*.

Species	Cover Type	Habitat Stage					
		1	2	3	4	5	6
American Marten	Pine			2	2	2	2
	White Spruce			2	3	4	6
	Mixed				2	3	4
Meadow Vole	Pine	3	2				
	White Spruce	6	3				
	Aspen	6	3				
	Mixed	6	3				
	Black Spruce	3	2				
Broad-Winged Hawk	Aspen					4	6
	Mixed				4	5	4
Three-Toed Woodpecker	Pine	4			2	4	5
	White Spruce				3	4	6
	Mixed				2	3	4
	Black Spruce	3			2	4	6
Black-Throated Green Warbler	White Spruce			2	4	5	4
	Mixed			2	4	6	6

3.0 Methodology

3.1 Projecting the Range of Natural Variability in Habitat Area

In recent years, governments and forestry companies in Canada have been moving away from the traditional objectives of sustained yield timber management, instead choosing to adopt sustainable forest management practices (Armstrong *et al.*, 2003). One of the most commonly used (or at least talked about) management styles is the natural disturbance model. Hunter (1993) provides a clear discussion of this management model. The central hypotheses of the natural disturbance model are that timber harvesting practices which emulate natural disturbances can be developed, and that harvesting timber in a way that emulates natural disturbance will allow for maintenance of biodiversity.

From an ecological standpoint, fire has been a disturbance agent on the landscape of the boreal forest for centuries, and is thought to be a significant process in the development of ecosystem biodiversity. Drawing from Armstrong (1999), one of the primary characteristics of the natural fire regime for the boreal mixedwood forest is a large interannual variability in annual area disturbed by fire. He characterizes the annual proportion of total area burned in his study as a random draw from a lognormal distribution. One of the outcomes of this characterization is that a long time series of annual area burned should show extreme fire years that occur relatively infrequently. The occurrence of these infrequent extreme events results in a non-equilibrium system (i.e. there is no equilibrium age-class structure for this forest). This means that any projection of the characteristics of this system, when subject to natural disturbance, should include some measure of the system's variability.

Following Armstrong *et al*. (1999, 2003), Monte Carlo simulations were used to project the probability distribution of habitat areas for each of the five vertebrate species. One thousand simulated inventory projections were run, each of which projected the development of the forest for 100 years. The starting point of each projection was taken to be the initial forest structure (Figure 1). In each year of each simulation, the annual burn rate (λ_t) was drawn from the lognormal distribution identified by Armstrong (1999).

$$\lambda_t = \min(0.20, \exp \chi), \;\; \chi \sim N(\mu\,, \sigma^2), \;\; t = 1, 2, \ldots, 100. \qquad (1)$$

These simulations use Armstrong's (1999) parameter estimates: $\mu = -8.096$ and $\sigma = 2.853$. These parameters are easily interpretable: μ is the mean of the natural logarithm of the annual proportion of the area burned under a natural disturbance regime; σ is the standard deviation. The annual proportion of area burned for this study was truncated at 0.20 in order to prevent burn proportions much greater than evident from the historical record. For a more detailed description of the steps taken in the simulation model, refer to Armstrong *et al.* (2003).

In this paper, the focus is on good habitat, that is, habitat with a quality index of five or greater. Figure 3 presents the good habitat projections for all five species. The panels of the figure show the 95% confidence limits and several quantiles for each of the projections, spanning over 100 years.

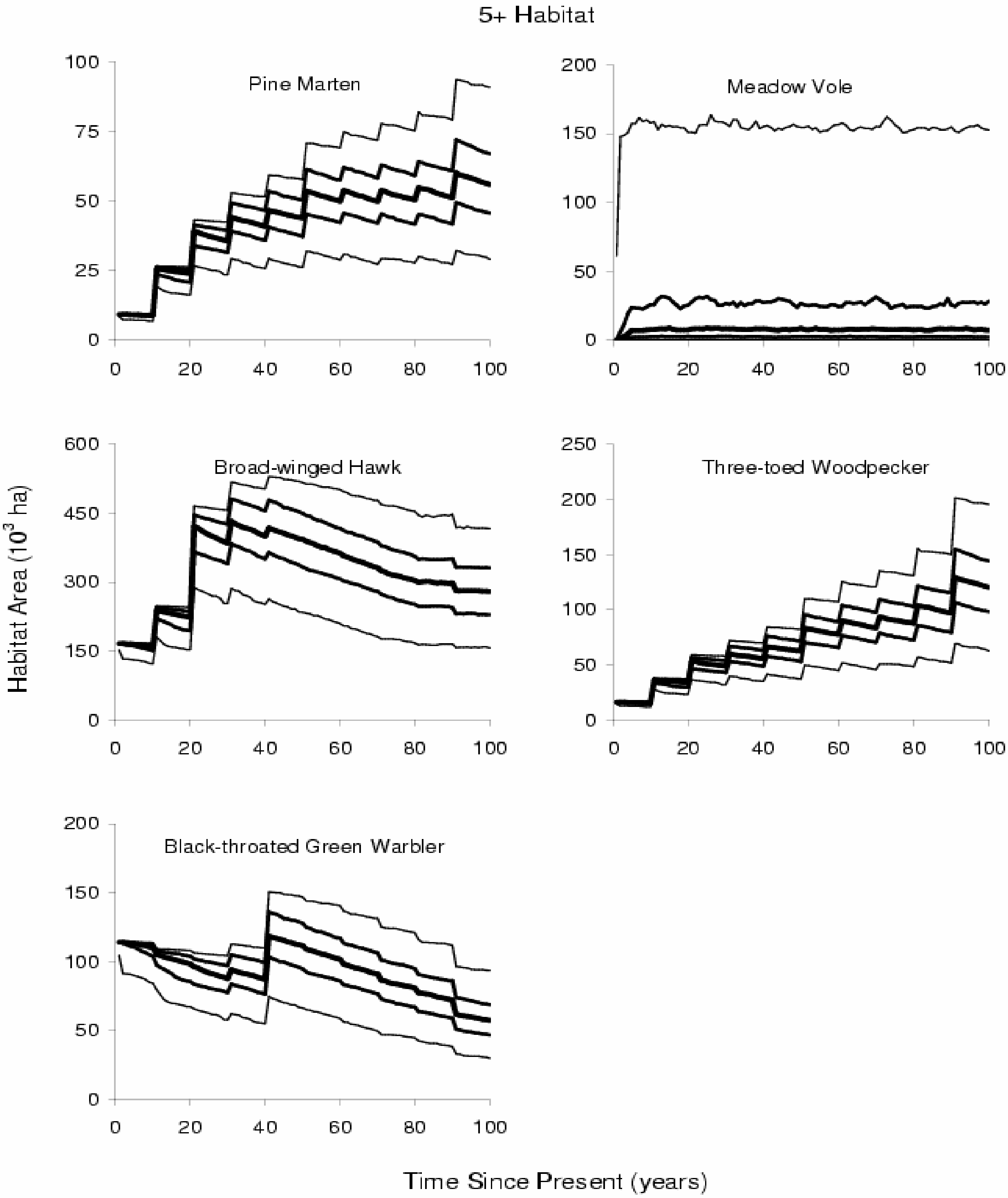

Figure 3: Habitat Projections for Areas of Good Habitat (Quality Index of 5+) Under Natural Disturbance. The Quantiles Shown are 2.5, 25, 50, 75 and 97.5.

The results depicted in Figure 3 present an interesting planning problem. Under the natural disturbance model of management, the goal is to maintain the characteristics of a natural ecosystem. However, the simulations conducted show that there is no one "ecologically correct" mix of habitats for the forest and that the realized mix of habitat areas is likely to change dramatically over time. Another consideration is that there are trade-offs between areas of habitat for the different wildlife species. For example, with the models used here, overmature white spruce is good habitat for American marten and three-toed woodpecker, but less than ideal for meadow vole, broad-winged hawk, and black-throated green warbler. Allowing white spruce stands to reach overmaturity delays the creation of new good habitat for meadow vole, broad-winged hawk and black-throated green warbler (Armstrong *et al.*, 1999; 2003).

3.2 Carbon Dynamics

The overall carbon balance of a forest landscape is determined by the past disturbance regime (as reflected by the current age-class structure) and by current growing conditions, disturbance patterns and forest management activities (Kurz *et al.*, 2002). Forest management activities, such as suppression of natural disturbances or changing harvest rotations, can have a significant effect on a forest's overall carbon balance (Kurz *et al.*, 1998).

Forest carbon stocks can be divided into two major pools; forest biomass (both aboveground and belowground) and dead organic matter (including detritus and soil organic matter). Changes in forest carbon pools are mainly driven by the dynamics of the living biomass. Varying proportions of carbon are then transferred from biomass to dead organic matter (DOM) pools as forests are subjected to different types of disturbances (Apps *et al.*, 2000). For example, harvest events remove the biomass in merchantable timber from the forest ecosystem, transfer faster decomposing foliage and branches to the DOM carbon pool, and release carbon to the atmosphere through disturbance of the ecosystem (Kurz *et al.*, 1998; Kurz and Apps, 1999).

In this paper, an attempt is made to realistically capture these carbon dynamics. Using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), separate biomass and DOM carbon yield curves are developed for implementation in the constrained optimization model described below (see section 3.3). These carbon yield curves capture carbon dynamics specific to individual forest cover types, stand age at time of harvest and the number of harvest events on a given stand. By integrating these yield curves into the optimization model, it is possible to capture the content of biomass and DOM carbon pools, carbon growth and decomposition rates and carbon transfers from biomass to DOM.[4]

The CBM-CFS3 provides a general framework for the dynamic accounting of carbon pools and fluxes in Canada's forest ecosystems (Kurz and Apps, 1999). It is designed to be consistent with current scientific understanding of forest carbon dynamics and compliant with evolving international carbon accounting rules (Kurz *et al*., 2002). Biomass accumulation curves derived from the national forest biomass inventory (Bonnor, 1985) and the 1986 Canadian Forest Inventory (Forestry Canada, 1988) are used to simulate aboveground biomass dynamics. Regression equations based on the literature are then used to derive belowground (root) biomass dynamics from aboveground biomass estimates (Li and Kurz, 2003). A simulation approach, based on stand dynamics, disturbance and management history and mean annual temperature, is used to estimate the size and composition of DOM carbon pools (Kurz and Apps, 1999).

3.3 Constrained Optimization Model

For the purposes of the optimization model, it is assumed that the objective of the forest manager is to maximize the net present value of timber harvest. Forest carbon management objectives will be introduced as constraints on the level of total carbon stocks. Concerns for non-timber values will be expressed as constraints on minimum areas of good wildlife habitat. Fire suppression occurs and is assumed to be 100% effective. Thus, the effects of fire in the optimization model are ignored.

The costs of carbon storage in a boreal forest ecosystem are explored using a Model II forest harvest scheduling model similar to that described by Johnson and Scheurman (1977). This structure is applied to an aggregated representation of a forest that includes a number of forest types and age-classes. The forest is managed by scheduling the various forest types and age-classes for harvest in different periods of an

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[4] Kurz and Apps (1999) identify these factors as the main indicators of carbon dynamics at the stand level.

X year planning horizon which is divided into discrete five year periods. The basic forest planning model may be written as follows:

Objective Function

$$\max_{x_{ijk},\, w_{ij}} \quad \sum_{i=1}^{I} \sum_{j=-M}^{k-M} \sum_{k=1}^{N} c_{ijk} x_{ijk} + \sum_{i=1}^{I} \sum_{j=-M_i}^{N} E_{ij} w_{ij} \tag{2}$$

Subject to

Area Constraints

$$\sum_{k=1}^{N} x_{ijk} + w_{ij} = A_{ij} \qquad \forall\ i, j \tag{3}$$

$$\sum_{l=k+1}^{N} x_{ikl} + w_{ik} - \sum_{j=-M}^{k-1} x_{ijk} = 0 \qquad \forall\ i, k \tag{4}$$

where

A_{ij} = area (ha) of forest type *i* born in period *j*,

$x_{ijk}(x_{ikl})$ = area (ha) of forest type *i* that is regenerated in period *j* (period *k*) and harvested in period *k* (period *l)*,

c_{ijk} = discounted net revenue ($/ha) generated by harvesting forest of type *i* born in period *j* and harvested in period *k*,

$w_{ij}(w_{ik})$ = area (ha) of forest type *i* regenerated in period *j* (period *k*) that is left as ending inventory at the end of the planning horizon,

E_{ij} = discounted value ($/ha) associated with the ending inventory of forest type *i* that is regenerated in period *j*,

N = the number of periods in the planning horizon,

M = number of periods before period zero in which the oldest age class present in period one was regenerated.

Most forest land in Canada is managed under highly regulated conditions. Here, regulation on timber flow is implemented as an even flow constraint on harvest volumes:

$$F_k = \sum_{i=1}^{I} \sum_{j=-M+1}^{k} v_{ijk} x_{ijk} \qquad \forall k \tag{5}$$

$$G_k = \sum_{i=1}^{I} \sum_{j=-M+1}^{k} z_{ijk} x_{ijk} \qquad \forall k \tag{6}$$

$$F_k - F_{k+1} = 0 \qquad \forall k \tag{7}$$

$$G_k - G_{k+1} = 0 \qquad \forall k \tag{8}$$

where

F_k = softwood volume (m^3) harvested in period *k*,

v_{ijk} = softwood harvest volume (m^3/ha) for forest type *i* that is regenerated in period *j* and harvested in period *k*,

G_k = hardwood volume (m^3) harvested in period *k*,

z_{ijk} = hardwood harvest volume (m^3/ha) for forest type *i* that is regenerated in period *j* and harvested in period *k*.

In this model, habitat levels for each of the five vertebrate species discussed above are tracked. Wildlife habitat suitability is related to the forest type and age of the forest. Habitat area constraints require that the area of good habitat in the forest is greater than a minimum level for all five species. These are:

$$\sum_{i=1}^{I} \sum_{j=-M+1}^{k} h_{ijks} x_{ijk} + h_{ijks} w_{ij} \geq \overline{H_{ks}} \qquad \forall k, s \tag{9}$$

where

h_{ijks} = habitat quality for species *s* in forest type *i*, birth period *j*, time period *k*,

$\overline{H_{ks}}$ = minimum level of habitat quality for species *s* in period *k*.

The coefficient h_{ijks} is set to one for each combination of development type, birth period and time period that has a habitat index of five or greater (good habitat) for vertebrate species *s*. For every other combination, h_{ijks} is set to zero.

Carbon dynamics for each of the forest cover types are also tracked. Constraints, requiring forest carbon stocks to be greater than a minimum level for all periods in the planning horizon, are formulated as:

$$\sum_{i=1}^{I} \sum_{j=-M+4}^{k} c_{ijk} x_{ijk} + c_{ijk} w_{ij} \geq \overline{C_k} \qquad \forall k \tag{10}$$

where

c_{ijk} = carbon stock (tonnes C) for forest type *i*, birth period *j*, time period *k*,

$\overline{C_k}$ = minimum stock of total forest carbon in period *k*.

Overall, an annual discount rate of 5% is assumed for the model. The conversion surplus value is assumed to be $60/m^3 for softwood timber and $50/m^3 for hardwood timber at the mill gate. As used here, conversion surplus is a measure of the value of logs delivered to the mill. It represents the selling price of the final product (i.e. lumber, pulp) less all the variable costs of milling and marketing the product, expressed on a per cubic metre of roundwood basis (Davis *et al*., 2001. pg 407). All softwood and hardwood volume is taken from every harvested stand. Stands are assumed to regenerate to the same cover type after harvest. No regeneration lag is modeled. Regeneration costs are assumed to be incorporated into the harvest costs. Timber harvest costs are assumed to be $5 000/ha. Even flow constraints are applied simultaneously to softwood and hardwood volumes: the harvest volume in any one period is constrained to equal the harvest volume from the previous period.[5] A set of model runs are also conducted without any harvest volume constraint, to simulate conditions which would allow managers to maximize their net present value.

The projected distributions of habitat (Figure 3) are used to set constraints on habitat levels for each of the wildlife species. Runs are made where the habitat area for all species are simultaneously constrained to be at least a specified quantile of the probability distribution of the area of good habitat in each of the periods of the planning horizon. The quantile constraint of 0.0 represents no habitat constraints (i.e. a pure timber emphasis run). The optimization problem is infeasible for all habitat constraint levels of 0.45 or greater. This means that it is not possible for the forest to simultaneously provide good habitat at or above this level for all five species over all periods in the planning horizon. Beyond this level, the habitat area for any one species can only be increased at the expense of another species (Armstrong *et al*., 1999; 2003).

Constraints on forest carbon stocks are set using the carbon yield curves developed with the CBM-CFS3. Carbon stocks are broken down into biomass and DOM

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[5] To check the sensitivity of results, the model runs with even flow constraints were compared to a set of runs conducted with an alternative harvest volume constraint: non-declining yield (NDY).

pools by forest cover type. Carbon transfers due to disturbance are related to forest type, stand age-class when harvested and number of harvest events on a given stand. The carbon contract modeled here requires the forestry firm to maintain at least a specified level of total forest carbon stock in each period of the planning horizon, starting from the third. The constraint level of 0.0 means no carbon constraint is enforced (again, allowing a pure timber emphasis). The optimization problem becomes infeasible for all carbon constraint levels of 245 million tonnes or greater. Additional model runs are conducted where various combinations of carbon level and habitat area constraints are simultaneously enforced.

The system is modeled using the Woodstock forest modeling package (Remsoft Inc., 1998) and solved using the linear programming (LP) solver in the MOSEK optimization tools software (MOSEK ApS, 2003). Woodstock provides a convenient way of specifying a forest management problem using a flexible syntax. It can generate a LP matrix as input to solution software such as MOSEK and translate the LP solution into easily understandable summary tables and graphs. A five year period, and a 25 period (125 year) planning horizon is used for all Woodstock models. The extra five periods (25 years) relative to the habitat simulations are added to the planning horizon in order to minimize the effect of end-of-planning-horizon timber anomalies. Such anomalies are typical of optimization-based timber harvest scheduling models without ending inventory constraints (Armstrong *et al*., 2003).

4.0 Results

Interestingly, results from the model runs show that carbon stocks would change over time even with carbon constraints imposed, as illustrated in Figure 4a. For this particular forest, with its specific cover types and initial age-class structure, carbon management causes carbon stocks to increase above the actual constraint level for the first few periods. Carbon stocks then gradually decline to the constraint level towards the end of the planning horizon. The reason for this overall trend is that managers can build up the DOM carbon pool by allowing the forest biomass carbon pool to increase during the initial few periods. Subsequently, as biomass is removed from the forest during the later planning periods, the increased DOM carbon pools are slower to react to this change in forest structure and thus maintain total carbon stocks above the constraint level. The decay rate of carbon from the DOM pools is slower than the removal of biomass through harvest activity. Figure 4b illustrates these dynamics for the 240 million t carbon constraint level.

Figure 4: Carbon Stock Projections

Figure 4a: Changes in Carbon Stock over Time by Carbon Constraint Level (No Habitat Constraints). Higher Curves are Associated with Higher Carbon Constraint Levels.[6]

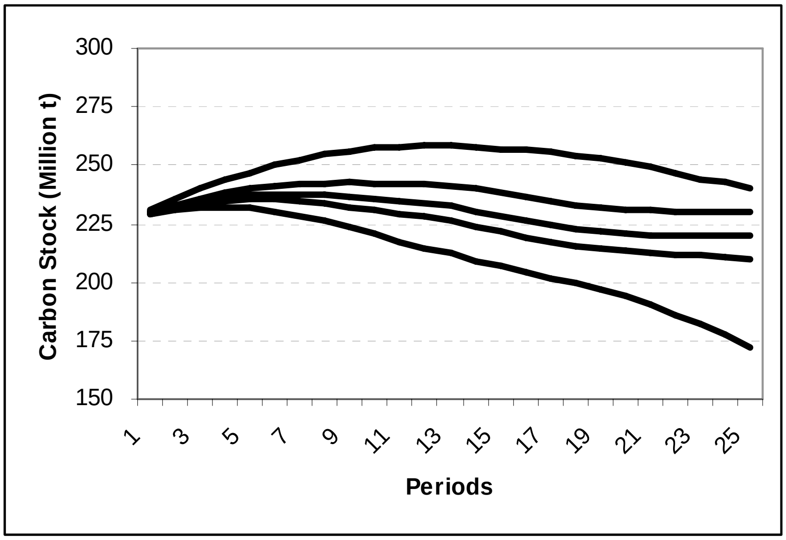
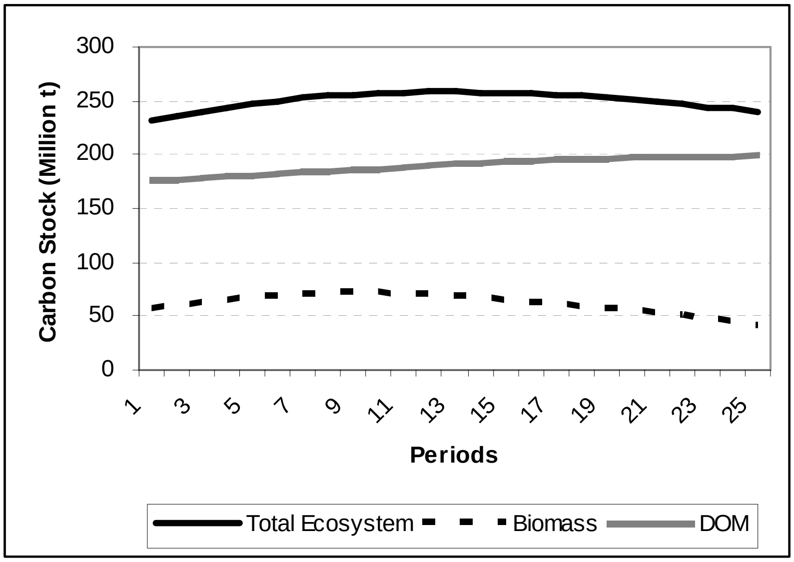


Figure 4b: Projected Carbon Dynamics for the 240 million t Carbon Constraint Level, Broken Down by Carbon Pool.



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[6] The curves represent constraint levels of 0, 210, 220, 230 and 240 million t of carbon, respectively.

The net present value (NPV) of timber harvest for each of the combined carbon level and habitat area constraints is presented in Table 3 below. As expected, the NPV decreases as the constraints become more binding. With no habitat constraints, requiring a 240 million t stock of carbon results in a 52.5% reduction in NPV from the pure timber emphasis run. The difference between the NPV resulting from a particular combination of carbon and habitat constraints and the NPV from the constraints a forestry firm currently faces could be viewed as the minimum contract price required to entice forest managers to adjust their harvesting practices.

The reduction in NPV is largely due to a decrease in the per period timber volume that can be harvested while still maintaining the required carbon levels and areas of good habitat. These reductions in harvest volume are substantial and would likely result in a reduction in the amount of labour and other inputs required by the forestry firm. This could have a significant impact on the local economy. The per period harvest volumes, under each of the combined carbon and habitat constraints, are provided in Table 4. Note that the even flow regulation means that harvest volumes are constrained to be the same in all periods of the planning horizon.

Table 3: Net Present Value (10^6 \$) by Carbon and Habitat Constraint Level.

Carbon Constraint (10^6 t)	**Percentile Habitat Constraint**			
	0	**2.5**	**25**	**40**
0	1358.6	1155.9	667.2	439.7
210	1192.4	1126.3	667.2	439.7
220	1100.6	1070.9	667.2	439.7
230	976.1	951.6	667.2	439.7
240	645.4	608.2	520.5	406.1

Table 4: Per Period Harvest Volume (10^6 m^3/yr) by Carbon and Habitat Constraint Level.

Carbon Constraint (10^6 t)	**Percentile Habitat Constraint**			
	0	**2.5**	**25**	**40**
0	10.34	8.76	6.19	4.39
210	8.87	8.43	6.19	4.39
220	8.16	7.95	6.19	4.39
230	7.10	6.98	6.19	4.39
240	4.27	4.16	3.81	3.35

One way to express the cost of carbon constraints is to divide the change in NPV from Table 3 by the change in the average carbon stock associated with the adjustment from a zero carbon stock constraint (or pure timber emphasis) to some other level. These costs are presented in Table 6a (for $/t C) and Table 6b (for $/t CO2).[7] With no wildlife habitat constraints, the cost of carbon constraints range from $16.65/t C ($4.54/t CO2) at the 210 million t constraint level to $20.77/t C ($5.67/t CO2) at the 240 million t constraint level. In order for the required change in forest management to be an efficient method of carbon sequestration, the value of stored carbon would have to exceed these values. Currently (January 2006), markets operating in Europe are trading carbon at approximately $30/t CO2.[8]

The other main point to note from the results in Tables 6a and 6b is that the costs of carbon constraints generally decline as the wildlife habitat constraints become more binding. This occurs for this forest because both types of constraints tend to preserve older timber. In fact, these costs drop to zero for all carbon constraints shown below 240 million t when habitat is constrained to the 25th percentile or higher. Carbon constraints in these cases do not bind since the required carbon stocks are met by default under the habitat area and even flow restrictions.

Table 6(a & b):$ per Average Change in Carbon Sequestered Under a "Permanent" Contract

Table 6a: Average Cost of Carbon Constraint ($/t C) by Carbon and Habitat Constraint Level.

Carbon Constraint (10^6 t)	**Percentile Habitat Constraint**			
	0	**2.5**	**25**	**40**
0	0.00	0.00	0.00	0.00
210	16.65	9.84	0.00	0.00
220	17.97	13.72	0.00	0.00
230	18.36	16.60	0.00	0.00
240	20.77	21.48	9.44	4.32

Table 6b: Average Cost of Carbon Constraint ($/t CO2) by Carbon and Habitat Constraint Level.

Carbon Constraint (10^6 t)	**Percentile Habitat Constraint**			
	0	**2.5**	**25**	**40**
0	0.00	0.00	0.00	0.00
210	4.54	2.68	0.00	0.00
220	4.90	3.74	0.00	0.00
230	5.01	4.53	0.00	0.00
240	5.67	5.86	2.57	1.18

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[7] For conversion: 1 unit of C = 3.6667 or 44/12 units of CO2 (44/12 is the ratio of the molecular weight of carbon to carbon dioxide).

[8] See the EU Price Assessment available at http://www.pointcarbon.com (cited January 25, 2006). Note, for comparison purposes, that the carbon costs derived in this study are in $ per average change in carbon sequestered under a "permanent" contract.

Similar trends can also be observed by examining the shadow prices of habitat constraints at differing levels of carbon stocks. The marginal cost of an extra unit of good wildlife habitat generally declines as carbon constraints become more binding. These shadow prices are provided in Table 7.

Table 7: Shadow Prices ($) of Habitat Constraints By Carbon Stock Level.

Carbon Constraint (10^6 t)	**Percentile Habitat Constraint**		
	2.5	**25**	**40**
0	9,237.39	35,520.01	49,118.20
210	6,342.77	35,520.01	49,118.20
220	2,334.32	35,520.01	49,118.20
230	1,544.71	35,520.01	49,118.20
240	2,827.69	28,323.17	44,476.45

Furthermore, results demonstrate the potential for co-benefits in non-timber resources to arise from forest carbon management. Figures 5 and 6, provided below, illustrate the tendencies for carbon constraints to affect wildlife habitat levels. Figure 5 depicts the model runs conducted without any harvest volume constraint, allowing managers to maximize their net present value of harvest. It can be seen here that good American marten habitat is eliminated almost immediately from the forest. This occurs because ideal marten habitat occurs in older white spruce stands, which are also prime candidates for logging due to the value and volume of timber held there. Meadow vole habitat also displays a unique relationship to carbon constraint levels due to that species' preference for open, recently disturbed forest. For the other three vertebrate species studied, however, definite co-benefits can be observed as the area of good habitat tends to increase as carbon constraints become more stringent. Moreover, Figure 6 shows that when harvest flow constraints are enforced these co-benefits may drive habitat areas even further within the natural range of variability.[9]

Incorporation of the even flow constraint (Figure 6) does produce one somewhat counter-intuitive result. When the 240 million t carbon constraint is enforced, the co-benefit effect appears to reverse for American marten and three-toed woodpecker in the early periods of the planning horizon, and for black-throated green warbler in later

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[9] Figure 6 depicts results when an even flow constraint was incorporated into the optimization model. Models run with non-declining yield (NDY) harvest flow constraints produced similar results.

periods. The area of good habitat for these species falls below that obtained under lesser carbon constraints.

What occurs when the 240 million t carbon constraint is applied in Figure 6 is a result of interactions between the conversion surplus, harvest flow regulation and carbon dynamics captured in the model. As discussed earlier, forest managers meet the carbon constraints by conserving biomass in early periods so as to increase transfers to the DOM carbon pool. The DOM pool is then used to maintain carbon stocks in later periods. In the carbon yield curves developed using the CBM-CFS3, deciduous and mixedwood stands generate larger DOM carbon pools than do coniferous stands.[10] Consequently, deciduous and mixedwood stands are conserved in early periods (creating good habitat for broad-winged hawk and black-throated green warbler), while relatively more valuable mature coniferous stands are harvested (reducing available habitat for American marten and three-toed woodpecker). In addition, harvesting mature deciduous stands can also cause a significant increase to DOM carbon pools through biomass transfer from decomposing foliage and branches. As a result, mature mixedwood stands are harvested in later periods in order to increase DOM carbon pools, as well as to capture their valuable softwood components. This reduces areas of good warbler habitat, but also affects the woodpecker since even flow constraints require the increased softwood volume to be displaced in other conifer stands of the forest (i.e. pine and black spruce). Three-toed woodpecker habitat thus increases as warbler habitat falls in later periods.

These "reverse" co-benefits are only observed when the 240 million t carbon constraint is applied. In this scenario, while the model has to conserve significant areas of forest in early periods of the planning horizon to increase carbon stocks, the even flow regulation causes it to also try and maximize NPV through the highest per period harvest volume possible. By explicitly modeling separate biomass and DOM carbon dynamics for each type of forest cover, the optimization model developed here allows this unusual behaviour to be captured.

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[10] For example, the foliage fall rates used by the CBM-CFS3 are 0.1 for softwood and 0.95 for hardwood.

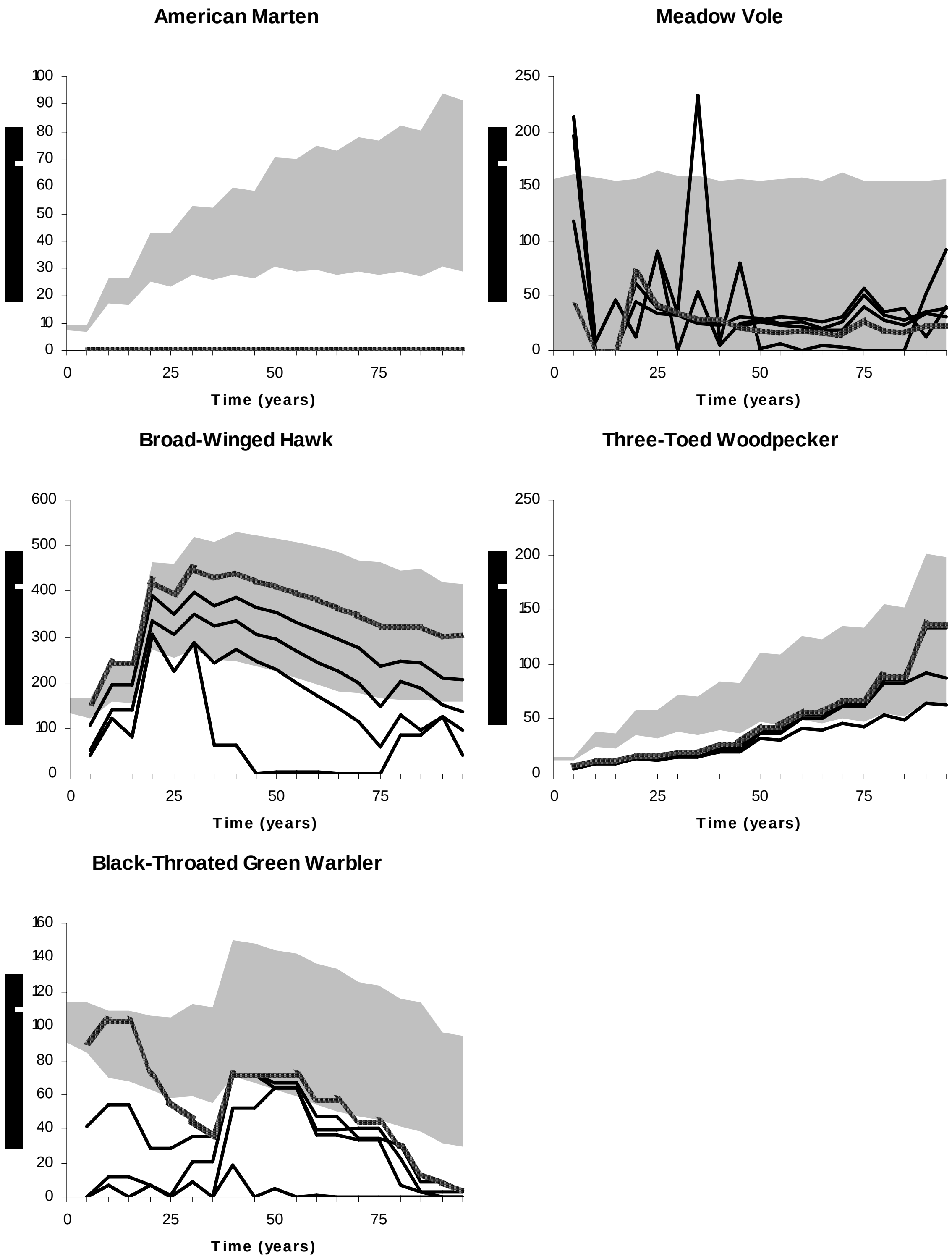

Figure 5: Projected Habitat Levels (10^3 ha) by Carbon Constraint Level (No Habitat Constraints) for Models Run without any Harvest Volume Constraint. Habitat Levels are Compared with the 95% Confidence Interval for the Projections of Natural Habitat (Gray Section). Carbon Constraints of 0, 210, 220 and 230 million t are in Black and the Higher Curves are Associated with Higher Carbon Constraints for all Species except Meadow Vole. The 240 million t (or Most Stringent) Carbon Constraint is in Dark Gray for Easy Identification.

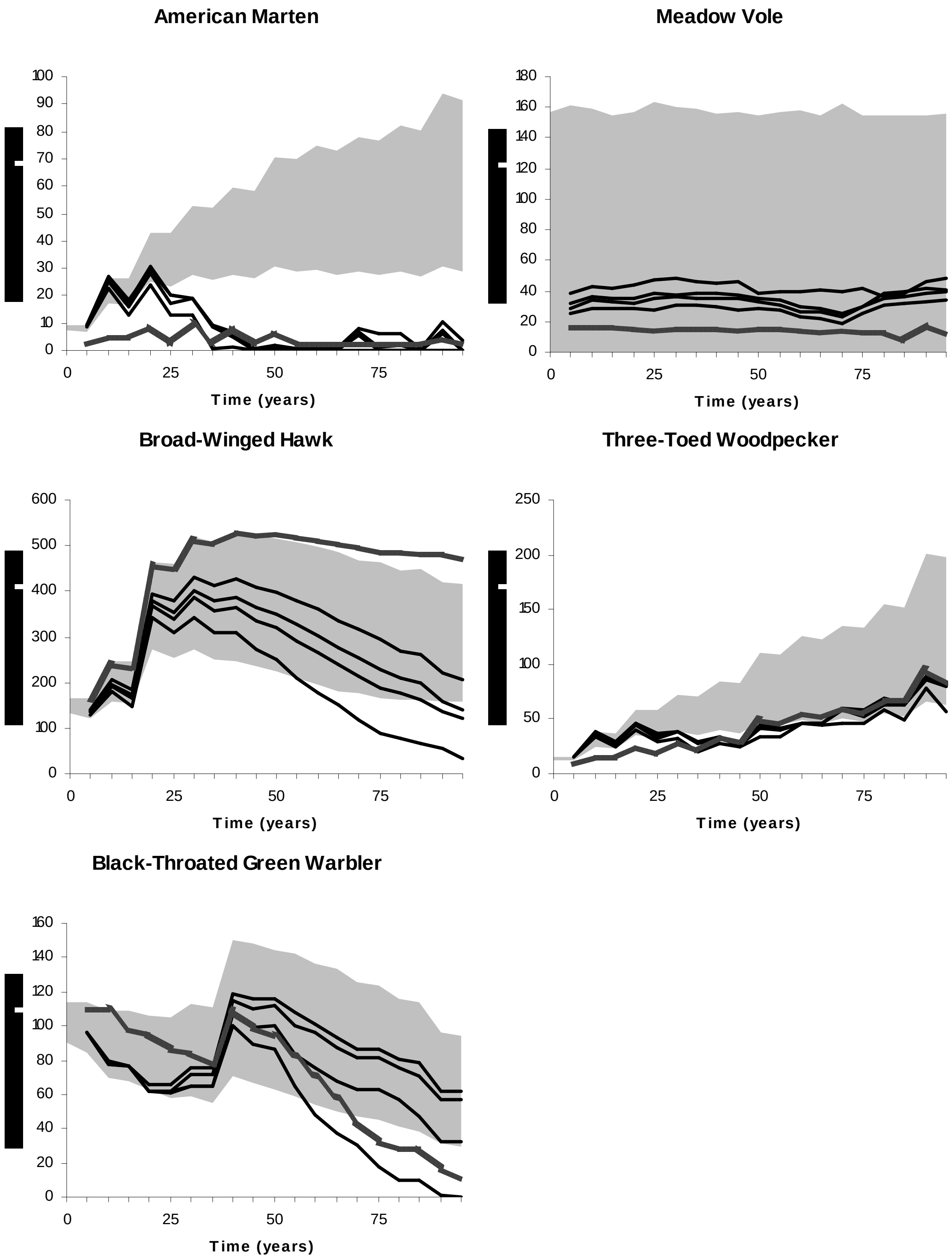

Figure 6: Projected Habitat Levels (10^3 ha) by Carbon Constraint Level (No Habitat Constraints) for Models Run with an Even Flow Harvest Volume Constraint. Habitat Levels are Compared with the 95% Confidence Interval for the Projections of Natural Habitat (Gray Section). Carbon Constraints of 0, 210, 220 and 230 million t are in Black and the Higher Curves are Associated with Higher Carbon Constraints for all Species except Meadow Vole. The 240 million t (or Most Stringent) Carbon Constraint is in Dark Gray for Easy Identification.

5.0 Discussion and Conclusion

This paper investigates the creation of a contract for carbon from a single forest management firm. This situation is assessed under the "realistic" conditions of a specific initial age-class structure, a regulatory constraint of even flow management and the existence of wildlife, or non-timber, constraints. Following the work of Armstrong *et al.* (1999, 2003), the non-timber constraints are entered along the lines of a coarse filter, natural disturbance approach to forest management. This allows for the inclusion of an element that has not typically been incorporated into such research: a representation of fire in the boreal forest ecosystem. These studies are then expanded upon by taking specific account of different dynamics in the biomass and DOM carbon pools of each forest cover type. It is believed that this case study provides insight into the expected response from forestry firms faced with the development of a market for carbon. In addition, the model is flexible enough to accommodate other forms of carbon contract, or other modifications to the production structure or environment, relatively easily.

An initial observation from the analysis is that forestry firms' willingness to accept for carbon may be well within the prices at which carbon in currently trading on existing markets. It should be noted, though, that these results likely provide a lower bound estimate given that the risk of removal of carbon due to fire has not been incorporated into the figures. Accounting for this risk factor would require the firm to ask for higher carbon sequestration payments. Furthermore, carbon costs as analyzed are in $ per average change in carbon sequestered under a "permanent" contract. For more fruitful analysis, this measure could be normalized for comparison with related studies.[11] In addition, results can also be related to the impact of carbon incentives on the supply of forest products. Firms that enter into agreements to sequester carbon may do so at the expense of a decline in timber supply and a reduction in related economic activity.

The main findings, however, concern the relationship between non-timber resources and carbon sequestration incentives. For this case study, carbon and non-timber resource scarcities move in the same direction. If the firm is required to constrain its operations in order to protect the most scarce wildlife habitat, this will be consistent

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[11] For example, Stavins and Richards (2005) attempt to devise a normalization procedure for comparison of the range of carbon sequestration costs in 11 different studies.

with the sequestration of carbon and will make the cost of doing so decrease. Conversely, the creation of incentives to sequester carbon will tend to reduce the costs of achieving non-timber objectives. This result is not surprising, perhaps, given that the scarcities in each case are older age-classes of forest.

Further examination shows that the creation of direct non-timber co-benefits through incentives for firms to sequester carbon may not be so straight forward. As implemented in the carbon contract system modeled here, a market for carbon may or may not generate a co-benefit by maintaining areas of good wildlife habitat. This relationship is shown to be dependent upon a particular species' preferred forest cover type, the specific biomass and DOM carbon dynamics associated with that cover type, the harvest flow regulation faced by the firm and the incentives for timber supply provided by the market. While these results are probably dependent upon the initial age-class structure and form of the carbon market, they nevertheless indicate that the impacts of carbon sequestration programs on non-timber resources should be an important element of policy analysis.

Several issues are not addressed here that could be incorporated into future research. The appeal of a carbon contract to a firm will largely depend on the disturbance history of their forest areas, as reflected in the existing age-class distributions. This may result in a number of forms of contracting depending on the heterogeneity in the industry, and these alternatives need to be examined. The risk of disturbance to the carbon stock, particularly fire, also needs to be incorporated into the analysis. Finally, this study does not include consideration of carbon storage in forest sector products, or the use of silviculture to enhance carbon sequestration. Both provide avenues for further refinement.

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