Optimal Harvest Decision Considering Carbon Stored in Forest and Wood Products, and Associated Fossil Fuel Carbon Emissions

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Abstract: In developing incentives and protocols to reduce carbon emissions and increase carbon sequestration, one important omission stands out. Policy makers have ignored or minimized the importance of carbon storage in wood products and the associated secondary emissions. In this paper, I present the results from a discrete dynamic programming model used to determine the optimal harvest decision for a forest stand that provides benefits from timber harvest, carbon sequestered in forest and carbon storage in wood products. This study is distinguishable from previous studies because it considers varying levels of starting dead organic matter (DOM) and wood product stocks. This is important because it allows one to establish a threshold level for determining if a landowner is better off participating in the type of carbon market considered in this study. The results of the study suggest that the optimal decision to harvest is independent on the carbon stocks in the wood product pool but significantly affects economic returns to carbon management. The results also indicate that economic returns decrease with increasing initial levels of...
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carbon in wood product and secondary carbon emissions have very little or no impact on the optimal decision to harvest. Contrary to the results from other studies, the results from this study reveal that increasing carbon price for a landowner to participate in the type of carbon market considered in this study will have the counterintuitive result of inducing the landowner to manage for carbon, if the wood product pool is considered.

1. Introduction

In developing incentives and protocols to reduce carbon emissions and increase carbon sequestration, one omission often stands out from the perspective of forest managers and forest product firms. Policy makers omitted wood product carbon, under the assumption that new wood products would simply replace discarded ones with no net change in this carbon pool (IPCC, 1997b). However, this is an over-simplification and not a realistic assumption about environmental conditions, because the new wood products do not simply replace the discarded ones. Harvested wood releases its carbon at rates dependent upon its method of processing and its end use: waste wood is usually burned immediately or within a couple of years, paper usually decays in up to 5 years (although landfiling of paper can result in longer-term storage of carbon and eventual release as methane or CO), and lumber decays in up to 100 or more years. Because of this latter fact, forest harvest could result in a net change of carbon if the wood that is harvested is used for long-term products such as building lumber.

Fortunately, there is now broad recognition that this assumption is faulty. As a result of the continuing debate, forward movement on the harvested wood product issue occurred in Copenhagen, including a report that detailed specifics regarding harvested wood product and the approach that countries may take to account for carbon storage in forests and wood products (UNFCCC, 2009). It is likely that a decision on the carbon storage issue will not be based on science alone. Politics
are certain to play an important role. For example, in the case of internationally traded wood, what nation should get credit for carbon stored in harvested wood products? Is the nation in which trees were grown, or the nation in which the wood is used? Which nation, should pay the penalty when products begin to decay and release carbon? These kinds of questions explain part of the reticence in dealing with the stored carbon issue.

To address this faulty assumption (all the carbon contained within trees is released at the moment of harvesting), a number of alternatives have been proposed. One of the proposals which is considered in this study, is the stock change approach. Canada is on record as supporting consistent national accounting for all sources and sinks within a national inventory. This position aligns with the stock change approach (UNFCCC, 2001). Under this approach, flows of wood are tracked, with carbon credits awarded when a country or landowner realizes a net positive change in stocks of harvested wood products. Conversely, a country or landowner that experiences a net loss of stocks of harvested wood products would be penalized. Accounting for stock changes in wood product pool has its challenges. It is hard to imagine how a landowner will retain ownership of wood carbon after a tree is harvested. This does not make sense and yet California climate action registry considers carbon sequestration associated with wood products. In December 2007, the Chicago Climate Exchange (CCX) Committee on Forestry approved new protocols for carbon sequestration associated with long-lived wood products and managed forests. These efforts may help inform international discussions about carbon storage in wood products (CCX, 2007).

The idea of crediting wood products is very controversial. It is seen by some in the scientific community that management regimes that reduce the standing stock of timber, even if they produce sustainable
timber harvest over time, will have smaller greenhouse gas (GHG) benefits than regimes that maintain a high volume of standing timber (Liski et al., 2001, Hoover and Stout, 2007). It is seen by some that without harvesting, very old stands will continue to build carbon reserves, particularly in the soil (Luysaert et al., 2008). They are of the opinion that climate policies should not encourage timber harvest and wood production as a means of reducing GHG emissions.

Despite the controversy, it is important to consider carbon storage in the wood product pool in developing an effective GHG reduction strategy because Canada supports “full carbon accounting that includes the accounting for carbon stored in harvested wood products and the CO₂ emissions and removals associated with harvested wood products”. It is also important to consider the wood product pool because it slows down the rate of growth of atmospheric CO₂ concentration. More importantly, wood products are critical to identifying major sources of CO₂ emissions so that policies can be developed to mitigate carbon emissions. Carbon storage in wood products could play an important role in climate change mitigation strategies and yet this role is little understood. Therefore, the main objective of this paper is to examine the impact of the wood product pool on the optimal behaviour of a landowner, where the landowner is described as an agent who controls both the forest and wood product.

A review of literature shows that harvested wood products can significantly extend the carbon sequestration benefits provided by forests (Dixon et al., 1994, Karjalainen, 1996, Skog and Nicholson, 2000). However, these findings can be misleading as they are only based on stock changes in harvested wood products and do not account for CO₂ emissions and removals associated with harvested wood products.

There is a fairly large body of literature on the biophysical aspect of carbon sequestration in wood products and fossil fuel carbon emis-
sions associated with carbon flows of wood products, but the economic aspect of the problem are still relatively unexplored. In the forest economics literature, van Kooten et al. (1995), assumed that a fraction of harvested timber (“pickling factor”) goes into long-term storage in structures and landfills. They used economic analysis to examine the effect of carbon taxes and subsidies on optimal forest rotation age and, consequently, the amount of carbon sequestered in a forest. However, there is no recognition of dead organic matter (DOM) in the van Kooten analysis. To the best of my knowledge, Gutrich and Howarth (2007) were the first to consider the amount of carbon stored in the DOM and wood product pools in determining the optimal rotation age. However, they did not consider the effect of different initial carbon stocks in the DOM or the wood product pools and they also did not account for fossil fuel carbon emissions associated with wood production cycle.

At the forest level, Hennigar et al. (2008) uses a model II linear programming formulation to simultaneously maximize carbon sequestered in live biomass, DOM and wood products. The results of their study showed that not accounting for wood products underestimates true forest contributions to carbon sequestration. Their wood products analysis did not address alternative CO₂ prices nor account for fossil fuel carbon emissions associated with wood products. The initial DOM and wood product stocks are fixed in their analysis.

Dynamic programming has emerged as a powerful approach to stand level optimization with respect to timber values and carbon sequestration. Spring et al. (2005b) formulated and solved a stochastic dynamic program to maximize the expected net present value of returns from timber production and carbon storage in a forest stand subject to stochastic fire. They modeled the decision problem using stand age as the only state variable: timber production and carbon storage were both treated as functions of stand age. In Spring et al. (2005a), the
same authors used stochastic dynamic programming to determine the rotation age considering timber production, water yield, and carbon sequestration under stochastic fire occurrence, again using stand age as the only state variable. Chladná (2007) used dynamic programming to examine the optimal forest stand harvest decision when timber and carbon prices are stochastic. Chladná used stand volume per hectare, timber price, and carbon price as state variables. Yoshimoto and Marušák (2007) optimized timber and carbon values in a forest stand using dynamic programming in a framework where both thinnings and final harvest were considered. In this case, the state variables for the problem were stand age and stand density (number of trees per ha).

In this paper, a dynamic programming model is developed to find the optimal stand management policy when both timber harvest and carbon sequestration values are considered. The state of the system at any stage can be described in terms of stand age and the quantity of carbon stored in both DOM and wood product pools. The management decisions available to the decision maker are to clearcut a stand of a given age, with a DOM pool of a given size and with a wood product pool of a given size, or to defer the harvest decision. Because a considerable proportion of carbon is stored in DOM relative to the total carbon stored by the stand and wood products have the ability to slow down the rate of CO$_2$ release back to the atmosphere, consideration of these two carbon pools could be of considerable economic interest. To the best of my knowledge, none of the stand level optimization models that consider timber harvest and carbon sequestration services have examined both the role of variable DOM carbon stock and variable wood product stock in determining the optimal harvest age.

A dynamic programming model was developed to:

1. examine the sensitivity of optimal harvest age to amount of car-
bon stored in the wood product pool and CO₂ prices,
2. examine the sensitivity of net present value to wood product stocks,
3. investigate the impact of fossil fuel carbon emissions on the optimal harvest decision, and
4. investigate the impact of ignoring the wood product pool on the optimal decision to harvest

2. The Model

Figure 1 is a schematic representation of the model developed for this study. It describes the flow of materials and energy through the wood product processing chain.

The figure shows that three main activities are involved in GHG emissions from fossil energy use. They include:

1. Stand establishment which involves seed and seedling production, site preparation and planting,
2. Harvesting, which is defined in this model to include road construction, logging and hauling of roundwood to mill, and
3. Processing, which is defined to include milling and transportation of finished product to consumers.

The wood product processing chain begins with stand establishment and ends with the decay of the wood product made from the trees. Using yield information from TIPSY for the lodgepole pine stand, approximately 40% of the total biomass is left behind at harvest and becomes part of the DOM pool. This means that logs removed from harvest represent approximately 60% of the total biomass and hence, carbon available for storage in long-lived products. This study is simplified by dealing with one relatively long-lived product (dimensional
Figure 1. Schematic representation of the carbon storage model.

The life cycle for wood product begins with the decision to harvest trees and ends with the decay of wood products made from those trees. Big oval boxes represent the pools of carbon in the living biomass, dead organic matter and wood products. The broken boxes represent the industrial forest carbon cycle which includes carbon emissions from forest management, transport, production, consumer use and disposal operations. Arrows represent carbon fluxes into and out of each pool. The cloud represents atmospheric carbon dioxide.
lumber for housing) and paper, which is assumed to be a very short-lived product. It is assumed that 100% of stored carbon in paper is emitted in the same year it is manufactured. The portion of the total biomass used for paper production is about 10%. This leaves approximately 50% of the total biomass available for processing lumber for housing. Of the remaining volume, an equivalent of 17% of the total biomass is lost as waste mainly through planing. This means that only 33% of the total biomass ends up in the housing pool.

In addition to carbon lost through decay of wood waste, establishment, harvesting and processing of wood product also requires fossil fuel energy.

To maintain credibility of the accounting system, the study boundary is clearly defined to include the flow of wood fibre from the BWBS biogioclimatic zone, in the Dawson Creek Timber Supply Area, in the Prince George Forest Region of British Columbia, and the carbon emissions associated with silviculture, harvest, transportation of wood fibre to the mill, milling, transportation of finished products to market and waste disposal.

This study assumes that a carbon market would develop in which an agent (landowner) with custody of both forest and wood product pool is paid for carbon added to the forest and wood product pools and pays when carbon is released. It is also assumed that the landowner will manage the forest jointly for timber production and carbon sequestration in the forest and wood products in a manner that earns maximum discounted financial return. The forest is managed using an even-aged silvicultural system. Each rotation begins with the establishment of a stand on bare forest land and ends with a clearcut harvest after a number of years of growth. The beginning of a new rotation coincides with the end of the previous rotation. The cycle of establishment, growth, harvest, and establishment is assumed to repeat ad infinitum.
2.1. Timber Yield and Costs

The growth and yield data as well as the cost information come from the TIPSY growth and yield simulator (BC MoFR) developed by the British Columbia Ministry of Forests and Range for use as input to forest management plans. The data used represent a lodgepole pine stand in the BWBS biogeoclimatic zone, in the Dawson Creek Forest District of the Prince George Forest Region of British Columbia, Canada. A medium site class (site index = 16 m at 50 years breast height age) and a planting density of 1600 stems/ha is assumed. The growth and yield data and other costs information generated from TIPSY are presented in Table 1. In the interest of saving space, the data in Table 1 are reported in decades, although the modelling was done on an annual basis.

The lumber values reported in Table 1, represent the total nominal lumber available for making $2 \times 4$s, $2 \times 6$s, $2 \times 8$s and $2 \times 10$s. The nominal size of a board varies from the actual size because of planing. The actual lumber size is estimated from the nominal size by using the conversion factors reported in Table 1. For example the actual size of a $2 \times 4$ is $1.5in \times 3.5in$ (38mm $\times$ 89mm). For a one board foot dimensional lumber, the conversion factor is calculated as: $(1.5 \times 3.5 \times 18)/(2 \times 4 \times 18) = 0.66$.

A derived residual value approach (Davis et al., 2001, p.418–427) is used to estimate the net value of timber harvest. All costs and prices in this paper are expressed in Canadian dollars (CAD). The residual value is the selling price of the final products (in this case lumber and pulp chips) less the costs of converting standing trees into the final products, expressed in CAD/ha of merchantable timber.

The average lumber price of kiln dried, standard and better, western spruce-pine-fir, $2 \times 4$ random length lumber for the period April 1999 to March 2008 was approximately 375 CAD/thousand board feet (MBF)
Table 1. Summary of data generated from TIPSY

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Volume (ri²/ha)</th>
<th>Biomass (tC/ha)</th>
<th>Chips (BDU/ha)</th>
<th>Lumber (bf/ha)</th>
<th>LRF (mbf/ha)</th>
<th>Conversion Factor</th>
<th>Log (CAD/ha)</th>
<th>Hauling (CAD/ha)</th>
<th>Milling (CAD/ha)</th>
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(BC MoFR, 2009). The price of wood chips was assumed to be 70 CAD/bone dry unit (BDU).

The selling price of lumber and chips expressed in terms of wood input at any harvest age \(a\) is represented by the parameter \(P^w_a\) (CAD/MBF) and \(P^x_a\) (CAD/BDU) respectively. The total revenue (CAD/ha) at any harvest age is calculated as \([P^w_a L(a) + P^x_a C(a)]\), where \(L(a)\) is lumber yield in MBF/ha and \(C(a)\) is chip yield in BDU/ha.

The cost of converting standing trees into end products is the sum of all costs associated with overhead, road construction, harvesting (tree-to-truck), hauling, and milling. Road construction and overhead costs reported by TIPSY for the pine stand were 1,150 and 2,500 CAD/ha respectively.

\(F(a)\) in CAD/ha is used to represent the cost (logging, hauling and milling) of converting standing trees of age \(a\) into end products. Stands are assumed to be reestablished immediately following harvest at a cost of \(E\) in CAD/ha.

### 2.2. Carbon Pool Dynamics

The TIPSY yield table is used as input to CBM-CFS3*1 in order to generate projections of carbon stored in each of the pools. A highly simplified representation of the carbon pool structure of CBM-CFS3 with just three carbon pools: a wood product pool, a biomass pool representing carbon stored above and below ground in living trees, and a DOM pool representing all other carbon stored in standing dead trees (snags), on the forest floor, and in the soil was created. The label DOM is used even though it is recognized that some of the carbon in this DOM pool is contained in living organisms. It is also assumed that

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*1 CBM-CFS3 (Carbon Budget Model of the Canadian Forest Sector) is a Windows-based software modelling framework for stand- and landscape-level forest ecosystem carbon accounting.
dimensional lumber used in housing is the only wood product since all the carbon stored in paper is assumed to be released in the year of manufacture. Therefore the total carbon stored $C_t$ at any given time $t$, measured in tC/ha is expressed in Eq.[1].

$$C_t = B(a) + D_t + Z_t$$

where $B(a)$ represents total carbon sequestered in the living biomass at age $a$; $D_t$ measures the total carbon sequestered in DOM pool in time $t$ and $Z_t$ represents carbon stored in wood product pool in time $t$. The mass of carbon in tC/ha, stored in the living trees at age $a$ is generated from CBM-CFS3 and presented in Table 1. Timber harvest is assumed to reset the age of the stand, and therefore its biomass, to zero. In this study, total carbon stored ($C_t$) in tC/ha refers to the sum of the wood product pool and total ecosystem carbon (TEC), where TEC is the sum of DOM and biomass pools.

Three processes are assumed to affect the development of the DOM pool: decay, litterfall, and harvest. DOM is assumed to decay at a rate, $\alpha$, which represents a fixed proportion of the DOM pool each year. DOM is added to the pool as the proportion of the biomass of the stand that dies naturally each year. This proportion is expressed as the litterfall rate, $\beta$.

With no timber harvest, the DOM pool grows according to Eq.[2].

$$D_{t+1} = (1 - \alpha)D_t + \beta B(a)$$

The decay and litter fall rates were estimated using the method of least squares to find the parameters $\alpha$ and $\beta$ which result in the closest match to the DOM projections produced from CBM-CFS3 using a pine stand. The estimated parameters are $\alpha = 0.00841$ and $\beta = 0.01357$. These parameters correspond reasonably well to the CBM-CFS3 projection. It is used to calculate forest carbon stocks and stock changes.
When timber harvest occurs, the merchantable timber volume is removed from the site and processed into lumber and wood chips. The roots, stumps, tops, branches and leaves are assumed to die at the time of harvest and become part of the DOM pool. The mass of carbon removed from the site as merchantable timber volume is calculated as $\gamma V(a)$ where $\gamma$ is a constant used to convert wood volume to the mass of carbon stored in wood. This study uses $\gamma = 0.2$, which is consistent with a carbon content of wood of approximately 200 kg m$^{-3}$ (Jessome, 1977). With timber harvest, the DOM pool grows according to Eq.[3]:

$$D_{t+1} = (1 - \alpha) D_t + B(a) - \gamma V(a)$$

The wood product carbon pool is represented by a single pool with a single annual decay rate of $\theta$. When there is no timber harvest, the dynamics of the carbon in the wood product pool is represented by Eq.[4]:

$$Z_{t+1} = (1 - \theta) Z_t$$

With timber harvest, the wood product pool grows according to Eq.[5]

$$Z_{t+1} = (1 - \theta) Z_t + q \gamma \lambda L(a)$$

where $\theta$ measures the decay rate for wood product; $q$ is factor that converts the nominal volume into actual volume; $\lambda$ is the factor that converts nominal lumber volume in thousand board feet into cubic metres of lumber; and $L(a)$ is the lumber volume in thousand board feet at age $a$.

Lumber is assumed to decay at a rate, $\theta$, which represents a fixed proportion of wood product pool each year. The decay rate was estimated using the method of least squares to find parameter $\theta$ which results in the closest match to the estimates of carbon remaining in lumber over time (Kurz et al., 1992). The estimates of carbon remaining over time are presented in Table 2. The estimated parameter is $\theta = 0.00578$. 


Table 2. Proportion of original carbon remaining in wood product (lumber) with time

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<th>Year</th>
<th>Lumber</th>
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<td>100</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Source: (Kurz et al., 1992)

The lumber decay rate, 0.00578 is comparable to other decay rates used in literature. Gutrich and Howarth (2007) estimated the decay rate of softwood lumber as 0.0038. McKenney et al. (2004) assumed a higher decay rate of 0.01 for lumber and other wood products.

Figure 2 shows the development of aggregated carbon pool stocks for a stand that is left unharvested (panel a) and one that is harvested on a 78 year rotation (panel b), given an initial age of 0 years, an initial DOM stock of 370 tC/ha and an initial wood product stock of 0 tC/ha. Panel (a) shows that in the early stages of stand development, the stand is a net source of CO₂ as a result of decay processes (Kurz et al., 1992). As the stand ages, the total carbon stocks increase with increasing biomass, and the decline in DOM stocks slows and reverses as carbon is added to the DOM pool in the form of litterfall, dead branches and natural tree mortality. Panel (b) illustrates what happens after a harvest. The figure shows that if a forest is planted and harvested periodically, carbon is fixed in the living trees during regrowth and put into storage in wood product and DOM carbon pools, which subsequently decays.
To account for fossil fuel carbon emissions, the following assumptions were made. It was assumed that fossil fuel carbon emissions from stand establishment and harvesting were 0.068 tC/ha and 0.273 tC/ha respectively (Gaboury et al., 2009). At the processing stage which is defined to include milling and transportation of finished product to consumers, fossil fuel carbon emissions was assumed to be 0.0212 tC/MBF for milling (Gower et al., 2003) and 0.0715 tC/MBF for transportation of finished product to consumers (Karjalainen and Asikainen, 1996).

Some studies have shown that logging and hauling operations are the highest GHG emitters of all forestry-related operations, before the pro-
cessing of wood products (White et al., 2005, Sonne, 2006). However, with the inclusion of wood products, it can be said that the main drivers of GHG emissions occur during the production of the wood product at the mill and during the transportation of the product to the consumers. It is also assumed that commercial timber is transported by truck to the mill, with an average highway travel time of 3 hours and the final product is transported to consumers by truck, with an average highway distance of 1,000 km.

2.3. Carbon Valuation

It is assumed that a carbon market exists in which a landowner with custody of both forest and wood product pool is paid for net sequestration of CO$_2$ and requires payment for net release of CO$_2$ in the previous year. Net carbon storage is calculated as the change in total carbon stocks (TEC and carbon in wood product pool) between periods $t+1$ and $t$ measured in tC/ha:

$$\Delta C_t = C_{t+1} - C_t$$

Carbon is presently not an active tradable commodity with a market price in Canada. The price received per tonne of sequestered CO$_2$ is the same as the price paid per tonne of released CO$_2$. A broad range of prices for CO$_2$ is used in sensitivity analyses. Prices of CO$_2$ ranging between 0 and 55 CAD per tonne of CO$_2$ (tCO$_2$) were examined. The price of permanent carbon credits traded on European Climate Exchange (ECX) between January 2005 and April 2008 ranged from 10 to 45 CAD/tCO$_2$ (Point Carbon, 2009). Prices for carbon credits traded on the Chicago Climate Exchange (CCX) for the same time period ranged from 1 to 5 CAD/tCO$_2$ (CCX, 2009). The range of prices used in this study encompass the range of observed prices.

It is conventional to express carbon prices in currency units per tCO$_2$ and stocks as tonnes of carbon (tC). The practice for reporting is con-
tinued here, but for modeling purposes, equivalent prices for carbon (CAD/tC) is defined as $P^C = 3.67P^{CO_2}$ because the molecular weight of CO$_2$ is approximately 3.67 times the atomic weight of carbon.

2.4. Dynamic Programming

The forest management problem modeled here is framed as a discrete backwards recursion dynamic program. The stages represent time, in one year time steps. The forest stand is described by a combination of three state variables, the age of the stand (years), carbon stocks in the DOM pool (tC/ha) and carbon stocks in the wood product pool (tC/ha). There are 251 discrete one-year wide age classes, $j$, with midpoints $a_j = j$, $j = 0, 1, \ldots, 250$ years. There are 101 DOM classes, $i$, with midpoints $d_i = 5i$, $i = 0, 1, 2, \ldots, 100$ tC/ha. There are also 101 wood product classes, $w$, with midpoints $n_w = 5w$, $w = 0, 1, 2, \ldots, 100$ tC/ha. Timber harvest volume and carbon stored in the biomass pool are calculated as a function of stand age.

For each state and each stage the possible decisions are to clearcut the stand immediately or postpone the harvest and let the stand grow for another year. If the landowner chooses to clearcut, immediate timber revenue will be realized. Both the clearcut and the leave decisions will result in a change in total carbon stock and the appropriate carbon credit or debit. If harvesting does occur (i.e., decision, $k = 1$) in stage $t$, it is assumed that replanting occurs immediately and the stand age is reset to 1 in stage $t + 1$. If harvesting does not occur (i.e., decision, $k = 0$) in stage $t$, the stand age is incremented by one year in stage $t + 1$.

The net change in carbon stocks, $\Delta C_{wijk}$ depends on current wood product class $w$, current DOM class $i$, age class $j$, and harvest decision $k$. It is the sum of the changes in wood product, DOM and biomass carbon pools.
For the no harvest case:

\[ \Delta C_{wij0} = B((\min(a_j + 1, 250)) - \beta B(a_j) - \alpha d_i - B(a_j) - \theta n_w. \]

For the harvest case:

\[ \Delta C_{wij1} = B(1) - \alpha d_i - \gamma V(a_j) - \theta n_w + q\gamma \lambda L(a). \]

The net harvest revenue for age class \( j \), \( (H_j) \) is calculated as

\[ H_j = \left[ P_w^w L(a) + P_x^w C(a) \right] - F(a) - E. \]

Establishment costs are included here because it is assumed that reforestation is required, and occurs, immediately after timber harvest.

The stage return or periodic payoff \( (N_t) \) is calculated as shown in Eq.[10]. The payoff is calculated for the midpoints of each wood product class \( (w) \), DOM class \( (i) \) and stand age \( (j) \) and for each of the possible harvest decisions \( (k) \). If a stand is not harvested \( (k = 0) \), the periodic payoff would be based on \( \Delta C_{wij0} \) only. If the stand is harvested \( (k = 1) \), the payoff is based on \( \Delta C_{wij1} \). This payoff is reduced by the total carbon emission charge \( (P^C M_T) \), which is the sum of the carbon release charge from stand establishment \( P^C M_E \), harvesting \( P^C M_H \) and processing \( P^C M_R \).

\[ N\{w, i, j, k\} = \begin{cases} 
P^C \Delta C_{wij0} & : \ k = 0 \\
(P^C(\Delta C_{wij1} - M_T) + H_j) & : \ k = 1 
\end{cases} \]

In this analysis, it is assumed the objective at each stage, is to determine, for each possible combination of stand age, level of carbon in wood product stock and level of carbon in DOM stock, the harvest decision that results in the maximum net present value of land and timber and carbon storage for the remainder of the planning horizon. The stages in this dynamic programming model correspond to the time periods in which decisions are made. It is a finite horizon, deterministic model with time \( t \) measured in years.
Because discrete DOM classes and discrete wood product classes are used, the projections from Eq. [2], [3], [4] and [5] are converted to the proportion of the source DOM and wood product class area that move into adjacent target DOM and wood product classes. \( d_{\text{wijk}} \) is used to represent the lower DOM target class, \( d_{\text{u}wijk} \) to represent the upper DOM target class, \( n_{\text{l}wijk} \) to represent the lower wood product target class, and \( n_{\text{u}wijk} \) to represent the upper wood product target class. \( \rho_{\text{wijk}} \) represents the proportion in the source DOM class and \( \sigma_{\text{wijk}} \) represents the proportion in the source wood product class. \( u \) is used to represent the proportion that moves into adjacent lower DOM class and adjacent lower wood product class; \( b \) to represent the proportion that moves into adjacent upper DOM class and adjacent lower wood product class; \( e \) to represent the proportion that moves into adjacent lower DOM class and adjacent upper wood product class; and \( f \) to represent the proportion that moves into adjacent upper DOM class and adjacent upper wood product class. Where \( u = \sigma_{\text{wijk}} \rho_{\text{wijk}}; b = (1 - \rho_{\text{wijk}}) \sigma_{\text{wijk}}; e = \rho_{\text{wijk}}(1 - \sigma_{\text{wijk}}); \) and \( f = (1 - \rho_{\text{wijk}})(1 - \sigma_{\text{wijk}}). \)

In the notation used here, \([x]\) indicates the floor of a real number \(x\), i.e., the largest integer less than or equal to \(x\). The fractional part of \(x\) is indicated by \(\langle x\rangle\) such that \(x = [x] + \langle x\rangle\).

\[\begin{align*}
\text{[11]} & \quad d_{\text{wij}0} = \min \left(\left[(1 - \alpha) d_i + \beta B (a_j)\right], 500\right) \\
\text{[12]} & \quad dl_{\text{wij}1} = \min \left(\left[(1 - \alpha) d_i + B (a_1) - \gamma V (a_j)\right], 500\right) \\
\text{[13]} & \quad d_{\text{wij}k} = \min \left(dl_{\text{wij}k} + 5, 500\right) \\
\text{[14]} & \quad n_{\text{l}wij}0 = \min \left(\left[(1 - \theta) n_w\right], 200\right) \\
\text{[15]} & \quad n_{\text{l}wij}1 = \min \left(\left[(1 - \theta) n_w + q \gamma \lambda L (a_j)\right], 200\right) \\
\text{[16]} & \quad p_{\text{u}wij} = \min \left(pl_{\text{wij}k} + 2, 200\right) \\
\text{[17]} & \quad \rho_{ij0} = \langle(1 - \alpha) d_i + \beta B (a_j)\rangle
\end{align*}\]
\[ \rho_{ij} = \langle (1 - \alpha) d_i + B (a_1) - \gamma V (a_j) \rangle \]

\[ \sigma_{ij} = \langle (1 - \theta) n_w \rangle \]

\[ \sigma_{ij} = \langle (1 - \theta) n_w + q \gamma \lambda L (a_j) \rangle \]

A weighted return is calculated from the target states associated with the harvest decision, \( k \).

For the no harvest decision, \( k = 0 \),

\[ W_{wij0} = u R^*_{t+1} \{ d_{wij0}, \min((j + 1), 250) \} + h R^*_{t+1} \{ d_{wij0}, \min((j + 1), 250) \} + e R^*_{t+1} \{ n_{wij0}, \min((j + 1), 250) \} + f R^*_{t+1} \{ n_{wij0}, \min((j + 1), 250) \}. \]

For the the harvest decision, \( k = 1 \),

\[ W_{wij1} = u R^*_{t+1} \{ d_{wij1}, 1 \} + h R^*_{t+1} \{ d_{wij1}, 1 \} + e R^*_{t+1} \{ n_{wij1}, 1 \} + f R^*_{t+1} \{ n_{wij1}, 1 \}. \]

The return for the last stage in the problem is initialized to zero.

\[ R_T \{ w, i, j, k \} = 0 \]

This assumption is justified on the basis that \( T \) is large (500 years) and the discounted value of \( R_T \) for reasonable discount rates for this problem is near zero (e.g., the present value of 1 CAD received 500 years in the future is \( 2.5 \times 10^{-11} \) CAD given a 5% discount rate).

The discount factor, \( \delta = (1 + r)^{-1} \), represents the relative value of a dollar received one year from now (given an annual discount rate of \( r \)) to a dollar today. The discount rate, \( r \), used for the analysis is 5% per annum: for this analysis, \( \delta = 0.9528 \). This rate is intended to reflect a market rate of time preference.

The recursive objective function for this problem is given in Eq.[24]

\[ R_t \{ w, i, j, k \} = \max_k N \{ w, i, j, k \} + \delta W_{wijk} \]

\( t = T - 1, T - 2, \ldots, 0 \)
The recursive objection function selects the harvest decision at each stage for each possible combination of state variables that maximizes the net present value at that stage, assuming that optimal decisions are made in all subsequent stages. It calculates a return for each of the harvest decisions and selects the harvest decision that results in the maximum return as the optimal choice for the state combination in that stage.

Equation [25] below modifies the stage return at time zero for stands of age 0, and represents the soil expectation value for each initial DOM and wood product class. This incorporates establishment costs for time zero. For subsequent stages, establishment costs are incorporated in Eq.[10].

\[
\forall w, i, j : R_0\{w, i, j, 0\} \leftarrow R_0\{w, i, j, 0\} - E - P^C M_E
\]

where \(M_E\), which is the net carbon emissions associated with stand establishment, measured in tC/ha.

3. Results and Discussion

In evaluating the economic feasibility of managing for both carbon and timber, a broad spectrum of scenarios have been investigated. A few general trends run throughout a large portion of the results, even though a number of the proposed scenarios differ subtly from one another. First, the sensitivity of optimal harvest age to the amount of carbon stored in the wood product pool and CO\(_2\) prices is examined. Second, the sensitivity of net present value to wood product stocks is examined. Third, the impact of fossil fuel carbon emissions on the optimal harvest decision is investigated. Fourth and finally, the impact of ignoring the wood product pool on the optimal harvest age is also investigated. The results presented in this section were calculated using an implementation of the dynamic programming model programmed in
MATLAB (Pratap, 2006).

To determine the impact of carbon stored in wood product pool on optimal harvest policy, two types of results are presented in Figure 3. Panel (a) shows the relationship between the current wood product stocks and the current stand age, and panel (b) shows the relationship between the current DOM stocks and the current stand age. In the interest of saving space, only two model runs with wood product stock held constant at 0 tC/ha and DOM stock held constant at 370 tC/ha are presented in this section. The amount of carbon in the DOM stock was held constant at 370 tC/ha because it is the initialized DOM carbon stock for lodgepole pine in the Dawson Creek Forest District, used in simulating the DOM stocks for this study. This value is close to 344 tC/ha, the (IPCC 2001) average estimated quantity of soil carbon in the boreal forest of Canada.

In Figure 3, the decision rule when \( P_{CO_2} \) is 0 CAD/tCO\(_2\) corresponds to the case when there is no incentives to manage for carbon: it is always optimal to harvest stands older than the Faustmann rotation age of 78 years, given the data used here. As \( P_{CO_2} \) increases, the optimal harvest age increases. When \( P_{CO_2} \) is 55 CAD/tCO\(_2\) or greater, the optimal decision is to never harvest. The results show that the optimal harvest policy is sensitive to the wood product stocks at the higher levels when carbon prices are high. This is because the amount of CO\(_2\) released to the atmosphere through decay is higher with higher wood product stocks. Hence, higher financial penalty is associated with higher wood product stocks. Therefore, at higher wood product stocks it is optimal to harvest early to minimize the financial penalties.

The results shown in panel (b) reveals that the optimal harvest policy is sensitive to DOM stocks at the lower levels when \( P_{CO_2} \) is 20 CAD/tCO\(_2\). This happens because the amount of CO\(_2\) released to the atmosphere through decay is lower with lower DOM stocks: the
marginal gain in CO₂ sequestration from delaying harvest is greater with lower DOM stocks.

Figure 4 displays a combination of stand age and wood product stocks that have the same value of land, timber and carbon sequestration services (LTCV, hereafter) for the entire state space, when $P_{CO₂}$ is 0, 2, 20, and 55 CAD/tCO₂. In these scenarios, the DOM carbon stock is also held constant at 370 tC/ha. Panel (a) represents the case where $P_{CO₂} = 0$. Because carbon has no value, in this case, the LTCV is independent of the amount of wood product stored. Notice from the results in Figure 4 that the contour lines are not smooth like those presented in Asante et al. (2011). This is because unlike Asante et al. (2011), functions were not used to represent the biomass and timber yield curves in this paper. Instead, tabular data from TIPSY and CMB-CFS3 which show sharp changes in gradient along the curves were used in this paper.

In general, the results presented in Figure 4 suggest that LTCV declines with increasing $P_{CO₂}$. Notice that for a landowner or agent who has custody of wood product stocks of about 200 tC/ha and a stand that is 100 years old, his/her LTCV declines from roughly 8,100 CAD/ha when $P_{CO₂} = 0$ CAD/tCO₂ to about 7,800 CAD/ha when $P_{CO₂} = 2$ CAD/tCO₂. It then declines to 3,200 CAD/ha when $P_{CO₂} = 20$ CAD/tCO₂, and finally to 1,800 CAD/ha when $P_{CO₂}$ is increased to 55 CAD/tCO₂. These findings contrast with results from other studies which generally show an increase in financial return when $P_{CO₂}$ is increased. The possible explanation is that there is a carbon emission charge associated with the decay of wood product and DOM decay. The magnitude of this charge becomes negative and large with increasing $P_{CO₂}$. Hence, for higher $P_{CO₂}$, the ability of the revenue from timber sale and carbon sequestration revenue to compensate for the carbon emission charge associated with the decay of wood product
and DOM decay decreases.

Figure 4 also reveals that LTCV decreases with increasing wood product stocks when the carbon price is positive. This might seem counterintuitive as more carbon storage is generally thought of as a good thing. However, a larger stock of wood product will generally release a greater absolute quantity of CO\textsubscript{2} to the atmosphere than a smaller stock. A large stock of decaying wood product is a liability for the decision maker represented in this model.

What differentiates this study from those of van Kooten et al. (1995), Spring et al. (2005a, 2005b), Chladná (2007), and Yoshimoto and Marušák (2007) is that fossil fuel carbon emissions were considered, whereas they ignore fossil fuel carbon emissions. Also wood product and DOM pools are considered in this study whereas they ignore these pools. In order to evaluate the effect of ignoring fossil fuel carbon emissions or wood product or DOM pools, a series of runs with a modified version of the model where the carbon market ignored fossil fuel carbon emissions or wood product or DOM pools were carried out. The results are summarized in Table 3.

In the range of scenarios that were analyzed, it is clear from the results that fossil fuel carbon emissions have very little impact on the optimal harvest decision except at high prices. In general, the optimal harvest age is older when fossil fuel carbon emissions are considered. The older harvest age is related to the fact that when harvest occurs, fossil fuel carbon emission charge associated with timber harvest reduces the net revenue generated from carbon sequestration. Hence, it is optimal to delay harvest in order to maximize net revenue generated from carbon sequestration.

LTCV as a function of wood product pool and stand age is presented in Figure 5. The results are based on a $P_{CO_2} = 20$ CAD/tCO\textsubscript{2} and DOM stock held constant at 370 tC/ha. The LTCVs show that there
(a) Relationship between current wood product stocks and current age. DOM stock is fixed at 370 tC/ha

(b) Relationship between current DOM stocks and current age. Wood product stock is fixed at 0 tC/ha

Figure 3. Optimal harvest policies for different carbon prices. The region to the right of and above the line corresponding to each carbon price represents the combinations of current age and current wood product or DOM carbon stock for which the optimal decision is to harvest. In the region to the left, the optimal decision is to delay harvest.
Optimal Harvest Decision Considering Carbon and Carbon Emissions

Figure 4. Land, timber, and carbon values (CAD/ha) by stand age and wood product stocks for different carbon prices

The contours indicate combinations of age and wood product states that have the same land, timber, and carbon values. The region where LTCV is positive is shaded grey. In these scenarios, the DOM carbon stock is held constant at 370 tC/ha.

is a difference between the scenario that considers fossil fuel carbon emissions and the scenario that ignores fossil fuel carbon emissions. Notice that for a stand age of 100 years and wood product stock of 100 tC/ha, the LTCV is about 3,900 CAD/ha when fossil fuel emissions are considered, compared to 4,800 CAD/ha when fossil fuel emissions are ignored. In this example, the difference is about 700 CAD/ha.

Based on the aforementioned results it can be concluded that when $P_{CO2} \leq 10$ CAD/tCO$_2$, carbon emissions have very little or no impact
on the optimal behaviour of the landowner but affects the financial returns considerably.

It is also evident from Table 3 that wood product carbon has very little or no effect on the optimal harvest decision except at high prices. It can generally be stated that the optimal harvest age is younger in the case when both DOM carbon and the wood product carbon are considered in carbon accounting compared to the case when the wood product carbon is ignored. This happens because the absolute amount of CO$_2$ released to the atmosphere through decay is greater when both DOM carbon and the wood product carbon are considered. As more CO$_2$ is released, there is little incentive to delay harvest because the marginal gain in timber revenue from leaving trees in the stand may not be enough to compensate for the repayment of carbon loss associated with the decay. Harvesting is done early to minimize financial penalty.

Because the optimal harvest decision barely changes when carbon storage in wood product is considered, it can be concluded that it is not worth the extra effort in carbon accounting given that the landowner's behaviour is not likely to change.

Figure 6 highlights the portion of the state space that shows wealth transfer from society to landowners without any noticeable benefit from mitigating the effect of GHG induced climate change when wood product pool is considered. These contours represent the difference between the LTCVs calculated when wood product stocks are considered and when they are ignored for $P^{CO_2} = 2$ and 20 CAD/tCO$_2$. There is transfer of wealth from society to landowners when the difference in LTCV is greater than zero. Figure 6 shows that wealth is transferred from society to the landowner if he/she owns a stand that is older than 100 years and has custody of wood product that is less than 100 tC/ha.

Figure 7 shows that a climate policy that encourages timber harvest as illustrated by 78 years harvest cycle and 102 years harvest cycle,
Optimal Harvest Decision Considering Carbon and Carbon Emissions

(a) Considers fossil fuel emissions. (b) Ignores fossil fuel emissions.

Figure 5. Comparison of land, timber, and carbon values (CAD/ha) by stand age and wood product stocks for a scenario.

Fossil fuel carbon emission is considered with one which ignores fossil fuel carbon emissions. The contours indicate combinations of age and wood product states that have the same land, timber, and carbon values. The region where LTCV is positive is shaded grey. In these scenarios, the initial DOM carbon stock is held constant at 370 tC/ha.

Table 3. Summary of optimal harvest ages and carbon stock with or without considering secondary carbon emissions for different carbon prices.

<table>
<thead>
<tr>
<th>Rotation age</th>
<th>No emission</th>
<th>No emission TEC</th>
<th>No emission TEC and product</th>
<th>With emission TEC and product</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{CO2}$ (CAD/tCO2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>78</td>
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<td>78</td>
</tr>
<tr>
<td>1</td>
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<td>81</td>
<td>79</td>
<td>79</td>
</tr>
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<td>102</td>
</tr>
<tr>
<td>30</td>
<td>∞</td>
<td>133</td>
<td>103</td>
<td>115</td>
</tr>
</tbody>
</table>

TEC refers to total ecosystem carbon, or the sum of DOM and biomass pools.
will result in a smaller quantity of total carbon storage over a 200 year period, compared to a climate policy that calls for no timber harvest. Over a 200 year period, total carbon storage is about 63,000 tC/ha when the rotation age is 78 years, 70,000 tC/ha when the rotation age is 102 years and 80,000 tC/ha when the decision is not to harvest.

\[
p_{\text{CO}_2} = 2 \text{ CAD/tCO}_2 \quad \text{(a)} \quad p_{\text{CO}_2} = 20 \text{ CAD/tCO}_2 \quad \text{(b)}
\]

Figure 6. Change in land, timber, and carbon values (CAD/ha).
Between the case when wood product pool is considered and the case when wood product pool is ignored for different carbon prices. The region of state space where the change is positive is shaded grey. In these scenarios, the DOM carbon stock is held constant at 370 tC/ha.

In addition to readily observable effects on carbon stocks, harvest operations can affect soil and forest floor carbon stores through physical disturbance. Harvesting can lead to overall carbon deficits in the first 20 years as immediate losses of carbon from DOM pool outweigh new growth and litterfall. Also, harvesting in the wet boreal forests with deep peat soils could trigger release of the vast amount of carbon stored in those soils.

This does not mean that harvesting is bad. In fire-prone forest, harvesting that reduces excess fuel loads may reduce the frequency or severity of fire, protecting forest carbon reservoirs into the future. Al-
though it is forest that actually removes carbon from the atmosphere, wood products play an important role by slowing down carbon release back to the atmosphere. Setting public policy will require weighing the advantages of accumulating more carbon in the forest versus the advantages of accumulating it in the housing pool or wood product pool.

4. Conclusions

The dynamic programming model proposed in this paper extends the existing literature on the determination of optimal harvest decision for a forest stand that provides both timber harvest volume and carbon sequestration services. The forest stand is described using three state variables: stand age and the stocks of carbon stored in the DOM and wood product pools. To the best of my knowledge, this is the first
paper to examine the impact of varying levels of initial wood product stocks and varying levels of initial DOM stocks on the optimal harvest decision. This study provides a basic framework for assessing the economic implications of accounting for carbon stocks in wood product. Some useful results from the analysis include:

1. Optimal harvest age increases with increasing CO\textsubscript{2} price.
2. The optimal harvest decision is sensitive to the current stocks of carbon in the wood product pool, when carbon prices are high and the wood product stocks are high.
3. The economic returns decrease with increasing wood product stocks.
4. Fossil fuel carbon emissions have very little or no impact on the optimal decision to harvest but affect economic returns to carbon management.
5. Wood products have very little or no impact on the optimal decision to harvest but affect economic returns to carbon management.

This study demonstrates that the optimal management policy does not change between cases where the market considers and ignores carbon storage in the wood product pool. It also demonstrates that fossil fuel carbon emissions have little or no impact on the optimal harvest policy. This raises an interesting concern whether it is worth the extra effort and cost to account for carbon stored in wood products and fossil fuel carbon emissions when the landowner’s behaviour is not likely to be affected? Policy makers may end up transferring wealth from society to landowners if they allow them to claim credit for carbon stock changes in wood products with no substantial change in behaviour.

The general results reported in this study can be expected to differ from forest-level analyses such as those reported by Hennigar \textit{et al}.
(2008) because of the effect of inter-period flow constraints imposed on forest-level models. The results can also be expected to differ from those reported in other stand-level models (e.g., van Kooten et al. (1995), Chladná (2007)) because it is recognized that the dead parts of forest (i.e., DOM and wood product) are a source. The results can also be expected to differ from other analyses because of the particular form of the carbon market assumed in this study. In this analysis, the landowner pays for emissions and gets paid for sequestration in the year of occurrence. Other market structures such as those based on the difference from a business-as-usual baseline or on a contracted amount of carbon storage at a particular point in time could lead to qualitatively different results.

It is important to note that complications to the carbon market considered in this study may come from market leakage and substitution effects, which are both outside the control of the offset system. For instance if the agent considered in this study lowers harvest levels in order to increase forest carbon, but a nearby landowner responds with increase timber harvest, leakage adjustments would have to be made to reduce creditable carbon stocks. Policy makers should be careful in designing a policy that encourages reduction in timber harvest. This is because such a policy may indirectly cause an increase in the use of substitutes such as concrete which emits more GHG in its production cycle.

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