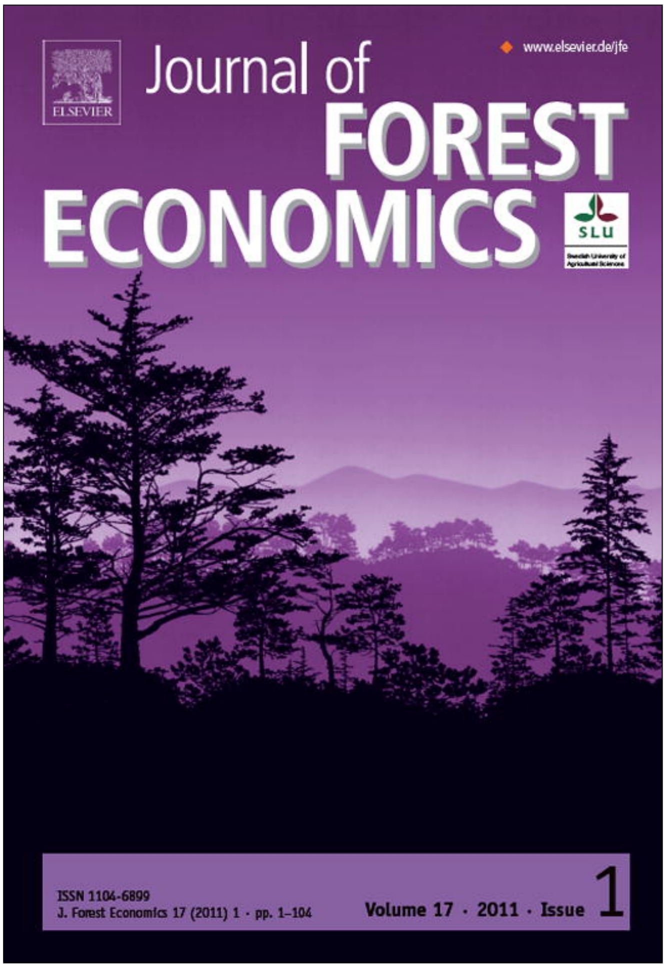
Carbon sequestration and the optimal forest harvest decision: A dynamic programming approach considering biomass and dead organic matter

Article *in* Journal of Forest Economics · January 2011

DOI: 10.1016/j.jfe.2010.07.001 · Source: RePEc

Wiktor Adamowicz
University of Alberta

Glen W. Armstrong
University of Alberta


www.elsevier.de/jfe
ELSEVIER
Journal of
FOREST
ECONOMICS
SLU
ISSN 1104-6899
J. Forest Economics 17 (2011) 1 · pp. 1–104
Volume 17 · 2011 · Issue 1

Journal of Forest Economics 17 (2011) 3–17

Contents lists available at ScienceDirect

Journal of Forest Economics

journal homepage: www.elsevier.de/jfe

Carbon sequestration and the optimal forest harvest decision: A dynamic programming approach considering biomass and dead organic matter

Patrick Asante[a], Glen W. Armstrong[a,*], Wiktor L. Adamowicz[b]

[a] Department of Renewable Resources, University of Alberta, Edmonton, Canada T6G 2H1
[b] Department of Rural Economy, University of Alberta, Edmonton, Canada T6G 2H1

ARTICLE INFO

Article history:
Received 14 August 2008
Accepted 14 July 2010

JEL classification:
C61
C63
Q22
Q23
Q53
Q54
Q57

Keywords:
Optimal rotation
Boreal forest
Carbon market

ABSTRACT

Carbon sequestration in forests is being considered as a mechanism to slow or reverse the trend of increasing concentrations of carbon dioxide in the atmosphere. We present results from a dynamic programming model used to determine the optimal harvest decision for a forest stand in the boreal forest of western Canada that provides both timber harvest volume and carbon sequestration services. The state of the system at any point in time is described by stand age and the amount of carbon in the dead organic matter pool. Merchantable timber volume and biomass are predicted as a function of stand age. Carbon stocks in the dead organic matter pool changes as a result of decomposition and litterfall.

The results of the study indicate that while optimal harvest age is relatively insensitive to carbon stocks in dead organic matter, initial carbon stock levels significantly affect economic returns to carbon management.

Introduction

In response to global concern about climate change, policy makers and scientists are searching for ways to slow or reverse the trend of increasing concentrations of greenhouse gases, especially carbon dioxide (CO_2), in the atmosphere. Forests are viewed as potential carbon sinks. As trees grow,

* Corresponding author at: University of Alberta, Department of Renewable Resources, 751 General Services Building, Edmonton, Alberta, Canada T6G 2H1. Tel.: +1 780 492 8221.

E-mail addresses: pasante@ualberta.ca (P. Asante), gwa@ualberta.ca (G.W. Armstrong), vic.adamowicz@ualberta.ca (W.L. Adamowicz).

1104-6899/$ – see front matter
doi:10.1016/j.jfe.2010.07.001

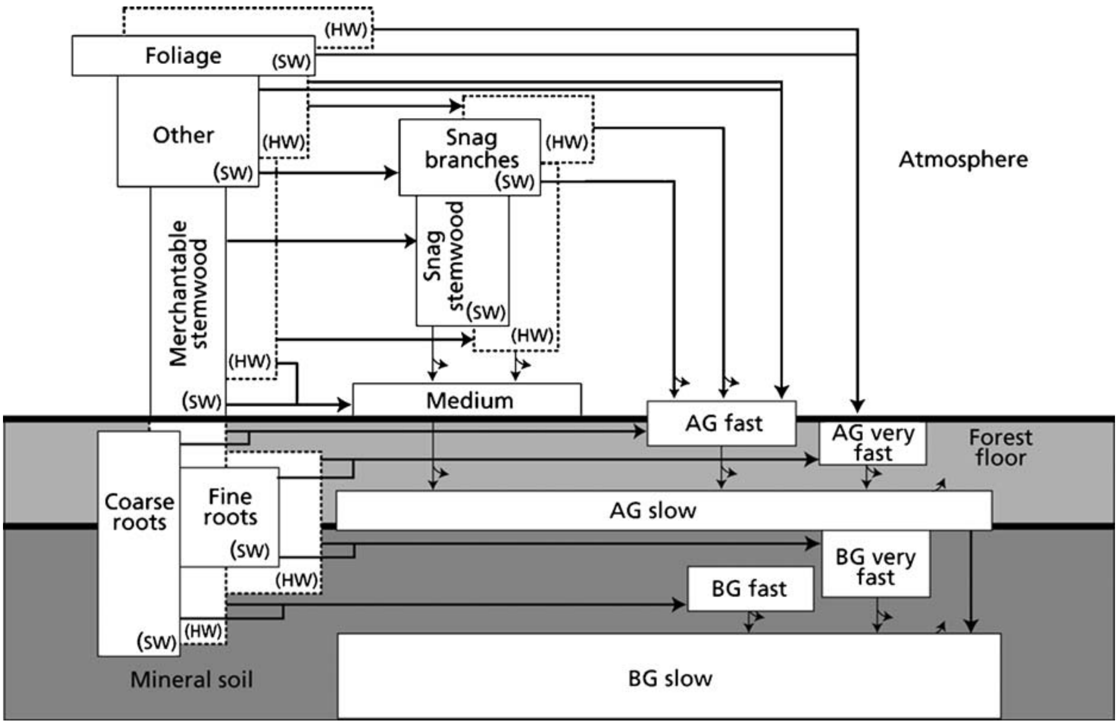


Fig. 1. The carbon pool structure of the CBM-CFS3. Very fast, fast, medium, and slow refer to relative decomposition rates for pools. Curved arrows represent transfers of carbon to the atmosphere, and straight arrows represent transfers from one pools to another. SW is softwood, HW is hardwood, AG is above ground, and BG is below ground. Illustration courtesy of the Canadian Forest Service, reproduced with permission from Kull et al. (2007, Fig. 1-1).

photosynthesis converts CO_2 into cellulose and other plant material, temporarily removing it from the atmosphere. In addition, a substantial amount of carbon is stored in forests as dead organic matter (DOM) in standing snags, on the forest floor, and in the soil until the process of decomposition releases it back to the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for the calculation and reporting of changes in stocks of forest carbon (IPCC, 2006) as it relates to national greenhouse gas inventories. The IPCC identifies three tiers for reporting changes in stocks of forest carbon. These tiers reflect the relative importance of forest carbon stocks to greenhouse gas inventories and the sophistication of the data collection and monitoring infrastructure of countries.

Canada has elected to use tier 3 methodologies (with the most detailed reporting requirements) for reporting changes to carbon stocks on managed forest lands. The IPCC specifies five carbon pools that must be accounted for: above-ground biomass, below-ground biomass, dead wood, litter, and soil carbon. The Canadian Forest Service developed the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to track and report changes in forest carbon stocks (Kull et al., 2007). CBM-CFS3 is a detailed model that recognizes more than 20 different carbon pools within a forest stand and tracks the transfer of carbon between these pools and the atmosphere (Fig. 1).

The classic problem in forest economics is the determination of the harvest age for an even-aged forest stand which maximizes the net present value of an infinite series of timber regeneration, growth, and harvest cycles. Faustmann (1849) is usually attributed with the first correct solution to this problem when only timber values are considered. Samuelson (1976) provides a more formal mathematical specification of the problem. Hartman (1976) extends the model to include values associated with standing trees (e.g. wildlife habitat) as well as the extractive value of timber harvest.

In the forest economics literature, most of the analysis of carbon sequestration has focused on the carbon pools in living biomass. However, the DOM carbon pool can represent a substantial proportion of the total carbon stored in forest stands and management decisions such as harvest age can have a substantial effect on soil carbon stocks (Aber et al., 1978; Kaipainen et al., 2004). Covington (1981) found that forest floor mass declines sharply following harvest, with about half of forest floor organic matter lost in the first 20 years. DOM may increase immediately following harvest as a result of slash and other debris left on site (Black and Harden, 1995). Despite the importance of the DOM pool in the carbon cycle of a forest stand, it has received limited attention in the literature on the economics of forest carbon sequestration, perhaps because of the difficulty of tracking a large number of carbon pools in an optimization model.

The Hartman model is used by van Kooten et al. (1995) in an early exploration of the effect of carbon prices on optimal forest harvest age in western Canada. In their analysis, the amount of carbon stored in the forest stand is proportional to volume of merchantable timber on the site at a particular stand age. The forest owner is paid for the accumulation of carbon in biomass associated with growth, and pays for carbon released to the atmosphere at harvest. Some of the harvested timber is assumed to be permanently stored in structures and landfills. There is no recognition of DOM or soil carbon in the van Kooten analysis.

Dynamic programming has been used in a some recent papers as an 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 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 Marusak (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).

Gutrich and Howarth (2007) developed a simulation model of the economics of timber and carbon management for five different forest types in New Hampshire, USA. Their model includes representation of carbon stored in live biomass, dead and downed wood, soil carbon, and wood products. Annual transfers of carbon between pools are modeled. For each timber type, an initial stock of carbon in the dead and downed wood pool is assumed. A grid search is performed to find the harvest age that maximizes net present value given the initial stock of carbon in the non-biomass pools. To the best of our knowledge, Gutrich and Howarth (2007), were the first to publish a study where the amount of carbon stored in the DOM pool was considered in determining the economically optimal timber harvest age. They do not, however, consider the effect of different initial stocks in the DOM pool.

At the forest level, McCarney (2007) uses a linear programming model which includes carbon stocks in both DOM and biomass pools in a model optimizing the net present value of timber harvest and carbon sequestration. Initial DOM stocks are fixed in McCarney's analysis.

In this paper, we develop a dynamic programming model to find the optimal stand management policy when both timber harvest and carbon sequestration values are considered. We describe the forest stand being modeled in terms of its age and the mass of carbon stored in the DOM pool. The management decisions available to the decision maker are to clearcut a stand of a given age and with a DOM pool of a given size, or to defer the harvest decision. Because the amount of carbon stored in the DOM pool is a substantial fraction of the carbon stored by the stand, consideration of the DOM pool could be of considerable economic interest. To the best of our knowledge, this is the first paper to examine the role of variable DOM stocks in the optimal forest harvest decision at the stand level.

As we demonstrate later in this paper, the size of the DOM pool controlled by a forest owner may affect the incentives associated with carbon management and the attractiveness of participating in carbon markets to forest landowners.

We use the dynamic programming model presented here to:

1. examine the sensitivity of optimal harvest age to stocks of carbon in DOM and carbon prices,
2. examine the sensitivity of the net present value of forested land to stand age, stocks of carbon DOM, and carbon prices,

3. examine projected trajectories of carbon stocks in DOM given optimal harvest rules for a given carbon price, and
4. examine the impact of ignoring carbon stocks in DOM on the optimal harvest decision.

Data

Timber yield and cost functions

The timber yield and the cost information used in this study come from the TIPSY growth and yield simulator (BC MoFR, 2007) developed and used by the British Columbia Ministry of Forests and Range for use as input to forest management plans. The data we use 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. We assume a medium site class (site index is 16 m at 50 years breast height age) and a planting density of 1600 stems/ha.

We approximate the tabular representation of the merchantable timber yield table from TIPSY using a Chapman–Richards growth function, $V(a) = \nu_1(1 - e^{-\nu_2 a})^{\nu_3}$, in which $V(a)$ represents the merchantable timber volume in m^3/ha at age a and ν_1, ν_2 and ν_3 are parameters, which were set at 500.4, 0.027 and 4.003 respectively. These parameters give an acceptable representation of the yield table generated by TIPSY.

All costs and prices in this paper are expressed in Canadian dollars (CAD). We use a derived residual value approach (Davis et al., 2001, pp. 418–427) to estimate the net value of timber harvest. 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/m^3 of merchantable timber.

The average lumber price of kiln dried, standard and better, western spruce-pine-fir, 2 × 4 random length lumber for the period April 1999 to March 2008 was approximately 375 CAD/thousand board feet (MBF) (BC MoFR, 2009). Based on the observed range of lumber prices for this time period, we also used low and high lumber prices (250 and 500 CAD/MBF) in sensitivity analyses (not reported here). The price of wood chips was assumed to be 70 CAD/bone dry unit (BDU). At 80 years of age (approximately the volume maximizing harvest age), the pine stand modeled with TIPSY will yield 0.210 MBF of lumber and 0.152 BDU of pulp chips per m^3 of roundwood input. The base selling price of the final products expressed in equivalent roundwood input terms is 89.40 CAD/m^3. The selling price of final products expressed in terms of wood input is represented by the parameter P^w. The total revenue (CAD/ha) at any harvest age is calculated as $P^w V(a)$.

The cost of converting standing trees into end products is the sum of all costs associated with harvesting, hauling, and milling. Road construction and harvesting costs reported by TIPSY for our pine stand were 1150 and 5100 CAD/ha. Log hauling, milling and overhead costs as 4.84, 34.65, and 8.06 CAD/m^3 respectively. The costs reported on a CAD/ha basis are assumed to be closely related to the area harvested; the costs reported as CAD/m^3 are assumed to be more closely related to volume harvested: we use F^a to represent area based costs and F^v to represent volume based costs. The total harvesting and processing costs at any harvest age (CAD/ha) are calculated as $F^a + F^v V(a)$. Based on the costs used here, we set F^a to 6250 CAD/ha and F^v to 47.55 CAD/m^3. Stands are assumed to be reestablished immediately following harvest at a cost, E, which we set to 1250 CAD/ha, based on the default parameters used by TIPSY.

Carbon pool dynamics

The TIPSY yield table was used as input to CBM-CFS3 in order to generate projections of carbon stored in each of the pools represented in Fig. 1. We create a highly simplified representation of the carbon pool structure of CBM-CFS3 with just two carbon pools: a biomass pool representing carbon stored above and below ground in living trees, and a dead organic matter pool representing all other carbon stored in standing dead trees (snags), on the forest floor, and in the soil. We use the label dead organic matter even though we recognize that some of the carbon in this DOM pool is contained in living organisms.

We estimate another Chapman–Richards function to represent the biomass carbon pool as a function of stand age: $B(a) = b_1(1 - e^{-b_2 a})^{b_3}$, where $B(a)$ is the mass of carbon in tC/ha, stored in the living trees at age a, and b_1, b_2, and b_3 are coefficients set at 198.6, 0.0253, and 2.64 respectively. This function provides a reasonable representation of the tabulated biomass at different stand ages from CBM-CFS3. Timber harvest is assumed to reset the age of the stand, and therefore its biomass, to zero.

Three processes are assumed to affect the development of the DOM pool: decomposition, litterfall, and harvest. DOM is assumed to decompose at a rate, α, 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. We express this proportion as the litterfall rate, β. With no timber harvest, the DOM pool grows according to Eq. (1).

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

The decomposition and litter fall rates were estimated using the method of least squares to find the parameters α and β which result in the closest match to the DOM projections of CBM-CFS3 for the pine stand. The estimated parameters are $\alpha = 0.00841$ and $\beta = 0.01357$. In general, the estimated curve corresponds well to the CBM-CFS3 projection.

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 γ is a constant used to convert wood volume to the mass of carbon stored in wood. We use $\gamma = 0.2$ 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. (2).

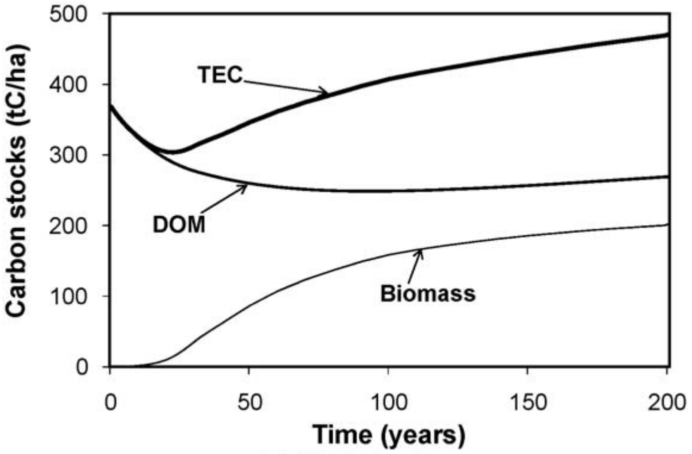
$$D_{t+1} = (1-\alpha)D_t + B(a) - \gamma V(a) \tag{2}$$

For the carbon market we assume here, the landowner is paid or pays for annual changes in stocks of total ecosystem carbon (TEC). The annual change in TEC is simply the sum of the changes in biomass and DOM carbon. With no harvest, the change in biomass is given by $\Delta B(a) = B(a+1) - B(a)$. With harvest, the age of the stand is set to 1 for the subsequent year, so the change in biomass becomes $\Delta B(a) = B(1) - B(a)$. The change in DOM for no harvest is given by $\Delta D_t = -\alpha D_t + \beta B(a)$. It is $\Delta D_t = -\alpha D_t + (1+\beta)B(a) - \gamma V(a)$ for the harvest case.

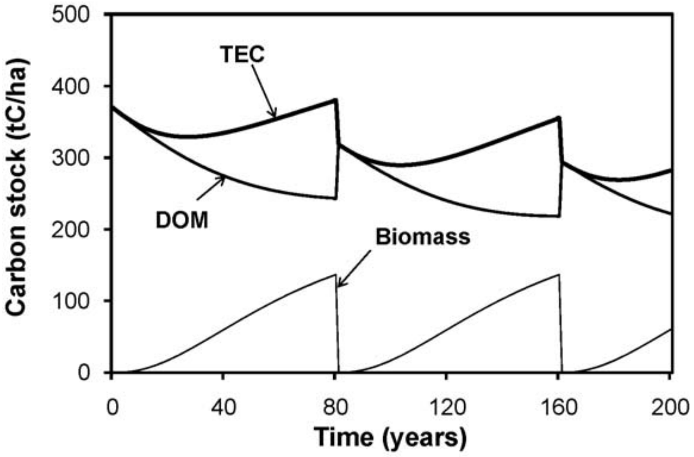
Fig. 2 shows the development of aggregated carbon pool stocks for a lodgepole pine stand that is left unharvested (panel a) and one that is harvested on an 80 year rotation (panel b) given an initial age of 0 years and an initial DOM stock of 370 tC/ha. In the early stages of stand development, the stand is a net source of CO_2 as a result of decomposition processes (Kurz et al., 1992). As the stand ages, TEC 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 the trajectory of C stock in the DOM pool after harvest. The figure shows that timber harvest on an 80 year harvest cycle produces a sharp increase in the amount of DOM at harvest, because of the input to the DOM pool of newly dead roots, stumps, tops, and logging slash.

Valuation of carbon

The carbon market posited here pays landowners for net sequestration of CO_2 and requires payment for net release of CO_2 in the previous year. The price received per tonne of sequestered CO_2 is the same as the price paid per tonne of released CO_2. In this study, we use a broad range of prices for CO_2 in sensitivity analyses. We examined prices of CO_2 ranging between 0 and 100 CAD per tonne of CO_2 (tCO_2). 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 we have chosen encompass the range of observed prices including any discounting that may occur in order to account for the temporary nature of carbon sequestration in forests. It is conventional to express carbon prices in currency units per tCO_2 and stocks as tonnes of carbon (tC). We continue the practice here for reporting, but for modeling purposes,



(a) No timber harvest.



(b) Timber harvest on an 80 year rotation.

Fig. 2. Projections of carbon pool development over time. Panel (a) is projection without harvest. Panel (b) is the projection with timber harvest on an 80 year rotation.

we define equivalent prices for carbon (CAD/tC) as $P^C = 3.67P^{CO_2}$ because the molecular weight of CO_2 is approximately 3.67 times the atomic weight of C.

The model

The basic assumption of the model is that a forest landowner is participating in a carbon market where the landowner is paid for carbon sequestered by the forest and pays when carbon is released. The landowner is assumed to manage the forest jointly for timber production and carbon sequestration 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, and harvest is assumed to repeat in perpetuity.

We represent the decision problem as a dynamic program, and use state variables to describe the system at each stage of the decision problem. It is theoretically possible to develop a dynamic program with state variables representing carbon stock in each of the more than 20 carbon pools represented in CBM-CFS3, but program solution becomes impractical due to Bellman's "curse of dimensionality" (Bellman, 1961). However, the two-pool representation of total ecosystem carbon we use here is easily formulated and quickly solved with dynamic programming.

Dynamic programming model

The model developed here is a discrete backwards recursion dynamic programming model. The stages represent time, in one year time steps. The forest stand is described by a combination of two state variables, the age of the stand (years) and carbon stocks in the DOM 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 501 DOM classes, i, with midpoints $d_i = i$, $i = 0, 1, \ldots, 500$ tC/ha. Timber harvest volume and carbon stored in the biomass pool are calculated as a function of stand age.

At each point in time, a decision is made by the landowner whether to clearcut the stand or let the stand grow for another year. Clearcutting yields immediate timber revenue. Both the clearcut and the leave decisions will result in a change in TEC 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 set 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 change in total ecosystem carbon, ΔC_{ijk} depends on current DOM class i, age class j, and harvest decision k. It is the sum of the changes in DOM and biomass. For the no harvest case:

$$\Delta C_{ij0} = B(\min((a_j + 1), 250)) + \beta B(a_j) - \alpha d_i - B(a_j). \tag{3}$$

For the harvest case:

$$\Delta C_{ij1} = B(1) + \beta B(a_j) - \alpha d_i - \gamma V(a_j). \tag{4}$$

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

$$H_j = (P^w - F^v)V(a_j) - F^a - E. \tag{5}$$

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

The stage return or periodic payoff (N_t) is calculated as shown in Eq. (6). The payoff is calculated for the midpoints of each 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 ΔC_{ijk} only. If the stand is harvested $(k = 1)$, the payoff includes payments or charges based on ΔC_{ijk} as well as the net revenue associated with timber harvesting, processing, and reestablishment.

$$N\{i, j, k\} = \begin{cases} P^C \Delta C_{ij0} & : \quad k = 0 \\ P^C \Delta C_{ij1} + H_j & : \quad k = 1 \end{cases} \tag{6}$$

In this analysis, we assume the objective at each stage is to determine, for each possible combination of stand age and level of 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 we are using discrete DOM classes, we convert the projections from Eqs. (1) and (2) to the proportion of the source DOM class area that moves into two adjacent target DOM classes. We use l_{ijk} to represent the lower target class, and u_{ijk} to represent the upper. We calculate ρ_{ijk} to represent the proportion that moves into the upper class and $(1 - \rho_{ijk})$ as the proportion that moves into the lower class. In the notation used here, $\lfloor x \rfloor$ 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 $x = \lfloor x \rfloor + \langle x \rangle$.

$$l_{ij0} = \min(\lfloor (1 - \alpha)d_i + \beta B(a_j) \rfloor, 500) \tag{7}$$

$$l_{ij1} = \min(\lfloor (1 - \alpha)d_i + \beta B(a_j) + B(a_1) - \gamma V(a_j) \rfloor, 500) \tag{8}$$

$$u_{ijk} = \min((l_{ijk} + 1), 500) \tag{9}$$

$$\rho_{ij0} = \langle (1 - \alpha)d_i + \beta B(a_j) \rangle \tag{10}$$

$$\rho_{ij1} = \langle (1 - \alpha)d_i + \beta B(a_j) + B(a_1) - \gamma V(a_j) \rangle \tag{11}$$

We calculate a weighted return from the target states associated with the harvest decision, k. For the no harvest decision, $k = 0$,

$$W_{ij0} = (1 - \rho_{ij0})R_{t+1}\{l_{ij0}, \min((j+1), 250)\} + \rho_{ij0}R_{t+1}\{u_{ij0}, \min((j+1), 250)\} \quad (12)$$

For the harvest decision, $k = 1$,

$$W_{ij1} = (1 - \rho_{ij1})R_{t+1}\{l_{ij1}, 1\} + \rho_{ij1}R_{t+1}\{u_{ij1}, 1\} \quad (13)$$

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

$$R_T\{i, j\} = 0. \quad (14)$$

We justify this assumption 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 2.5×10^{-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 is the rate is intended to reflect a market rate of time preference.

The recursive objective function for this problem is given in Eq. (15).

$$R_t\{i, j\} = \max_k N\{i, j, k\} + \delta W_{ijk}, \quad t = T-1, T-2, \ldots, 0 \quad (15)$$

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.

Eq. (16) below modifies the stage return at time zero for stands of age 0, and represents the soil expectation value for each initial DOM class. This incorporates establishment costs for time zero. For subsequent stages, establishment costs are incorporated in Eq. (6).

$$\forall i: \quad R_0\{i, 0\} \leftarrow R_0\{i, 0\} - E \quad (16)$$

Results and discussion

We use the dynamic program presented above to determine the optimal harvest policy for a profit-maximizing landowner managing a forest stand for production of wood volume and sequestration of CO_2. The optimal policy is summarized by a decision rule which shows the combinations of stand age and DOM states for which the optimal decision is to harvest, and those combinations for which the optimal decision is to defer harvest until at least the next period. We examine the change in policy in response to changing prices for CO_2 storage and also to according to alternative methods of accounting for DOM. The results presented in this section were calculated using an implementation of the dynamic programming model programmed in MATLAB (Pratap, 2006).

The optimal harvest policies for a number of different carbon prices are presented in Fig. 3. The decision rule when P^{CO_2} is 0 CAD/tCO_2 corresponds to the case when timber is the only value considered: it is always optimal to harvest stands older than the Faustmann rotation age of 73 years given the data we used here. As P^{CO_2} increases, the optimal harvest age increases. When P^{CO_2} is 35 CAD/tCO_2 or greater, the optimal decision is to never harvest. The optimal policy is sensitive to DOM stocks at the lower levels. This happens because the amount of CO_2 released to the atmosphere through decomposition is lower with lower DOM stocks: the marginal gain in CO_2 sequestration from delaying harvest is greater with lower DOM stocks.

Fig. 4 shows the decision rule for $P^{CO_2} = 30$ CAD/tC as the shaded grey area. The optimal decision is to harvest when the combination of DOM and age falls within this part of the state space. This figure also shows how two stands with different initial states would develop given this decision rule. The initial state in panel (a) is a stand that is 50 years old with initial DOM stocks of 370 tC/ha. It grows until it reaches 139 years, at which point it is harvested and regenerated on a continuing 139 year cycle.

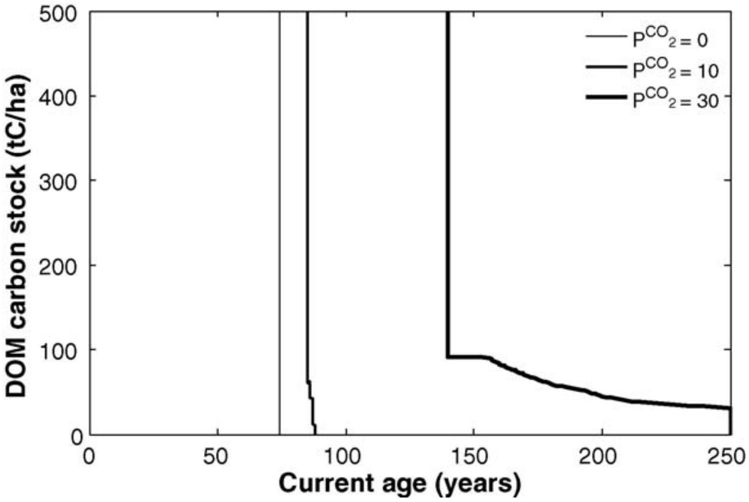


Fig. 3. Optimal harvest policies for different carbon prices. The region to the right of and above the line corresponding to each carbon price represents the combinations of current age and DOM carbon stock for which the optimal decision is to harvest. In the region to the left of and below the line, the optimal decision is to delay harvest. For carbon prices of 35 CAD/tCO_2 or greater, it is never optimal to harvest.

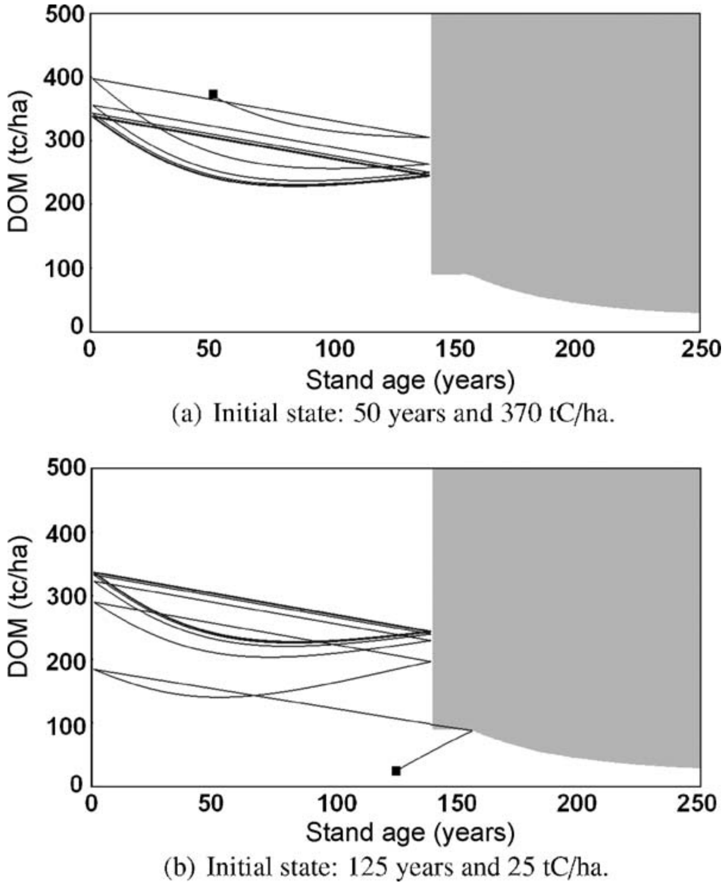


Fig. 4. Decision rule for P^{CO_2} = 30 CAD/tCO_2 with trajectories of stand development in state space. The grey polygon indicates the portion of the state space where the optimal decision is to harvest. The initial state is indicated by the small square. The lines indicate the state space trajectories. As the stand ages, it moves to the right on the *x*-axis, and the size of the DOM pool changes as a result of decomposition and litterfall. When the stand moves into the grey polygon, it is harvested. In the following year, the age of the stand is set to one year and DOM is increased from the pulse of input from the portion of biomass left on site after harvest.

Table 1
Summary of harvest age and carbon stock and mean annual increment equilibria for different carbon prices. DOM and TEC are equal at age 0 because there is zero biomass at this point. DOM refers to the amount of carbon stored in the dead organic matter pool. TEC refers to total ecosystem carbon, or the sum of DOM and biomass pools.

P^{CO_2} (CAD/tCO_2)	Rotation age (years)	DOM and TEC at age 0 (tC/ha)	DOM at rotation (tC/ha)	TEC at rotation (tC/ha)	MAI (m^3/ha/yr)
0	73	257	186	313	3.76
1	74	260	187	314	3.77
2	75	261	188	317	3.79
5	78	265	191	324	3.82
10	84	275	197	339	3.85
20	101	298	214	374	3.78
30	139	338	244	428	3.27

After the third harvest, the stand reaches an equilibrium condition where the DOM at the beginning and end of each rotation is essentially constant from one rotation to the next. The starting point in panel (b) is 125 years of age and 25 tC/ha of DOM. The first harvest occurs at a older age (150 years), but after the third or fourth harvest, the same equilibrium is reached.

Table 1 summarizes the equilibrium conditions for different carbon prices. A higher P^{CO_2} gives a longer rotation, with prices 35 CAD/tCO_2 resulting in a condition where the optimal decision is to never harvest. Because of the longer rotation age, carbon stocks are greater at both age zero and the rotation age with higher carbon prices. The variation in equilibrium rotation ages and carbon stored is substantial across the range of P^{CO_2} examined.

The MAI column in Table 1 refers to the mean annual increment of the stand. MAI is used by foresters to describe the productivity of a stand in terms of average annual physical product output for different rotation ages. It is calculated as $MAI = V(R)/R$ where R is the chosen rotation age. For the yield table we use in this study, the MAI is maximized at 87 years, which is close to the equilibrium rotation age when $P^{CO_2} = 10$ CAD/tCO_2. The MAI is irrelevant to the decision maker modeled in this paper, but may be relevant to society as a whole. Forest products such as lumber can serve as stores of carbon. There may be an advantage to choosing a harvest age that provides a larger MAI, and therefore more lumber production, if the carbon storage potential of wood products is taken into account. We defer exploration of this for a subsequent study.

Fig. 5 summarizes $R_0\{d_i, a_j\}$ from Eq. (15): the value of land, timber, and carbon sequestration services (LTCV, hereafter) for the entire state space, for carbon prices of 0, 2, 10, and 40 CAD/tC. Panel (a) represents the case where $p^{CO_2} = 0$. Because carbon has no value, in this case, the LTCV is independent of the amount of DOM stored.

In Fig. 5, P^{CO_2} has been set to 40 CAD/tCO_2 where the optimal decision is to permanently defer timber harvest. Note that for DOM stocks of above about 380 tC/ha, there is no stand age where this stand has a positive LTCV. If the decision maker had a choice of participating in this carbon market at this P^{CO_2}, or not, he would be unlikely to do so unless the initial state of DOM was less than 380 tC/ha as all positive LTCVs occur at DOM levels below this. This threshold is very near the IPCC (2000) estimate of average carbon stocks of 340 tC/ha in the boreal forest.

For intermediate carbon prices of 2 and 10 CAD/tCO_2, the picture is somewhat complicated (Fig. 5). Young stands with low DOM stocks have a greater LTCV than they would have with $P^{CO_2} = 0$. The DOM stocks would have to be lower than about 300 tC/ha for the decision maker to see any advantage in participating in this carbon market. The cost associated with paying for carbon released from decomposing DOM stocks is too high in much of the state space to make participation in such a market worthwhile.

Fig. 5 shows that LTCV decreases with increasing DOM stocks when the carbon price is positive. This might seem counter-intuitive as more carbon storage is generally thought of as a good thing. However, a larger stock of DOM will generally release a greater absolute quantity of CO_2 to the atmosphere than a smaller stock. A large stock of decomposing dead organic matter is a liability for the landowner represented in this model.

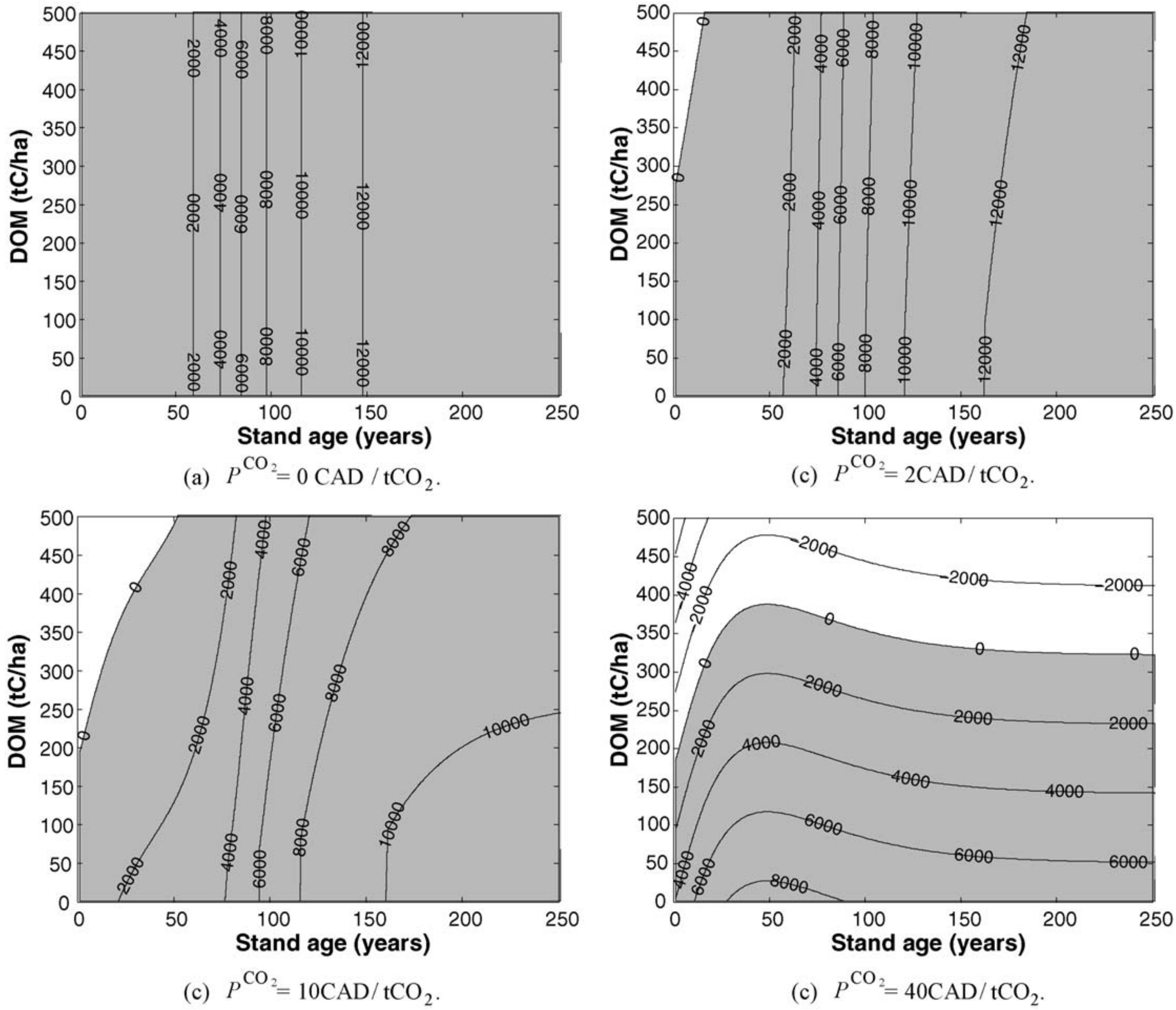
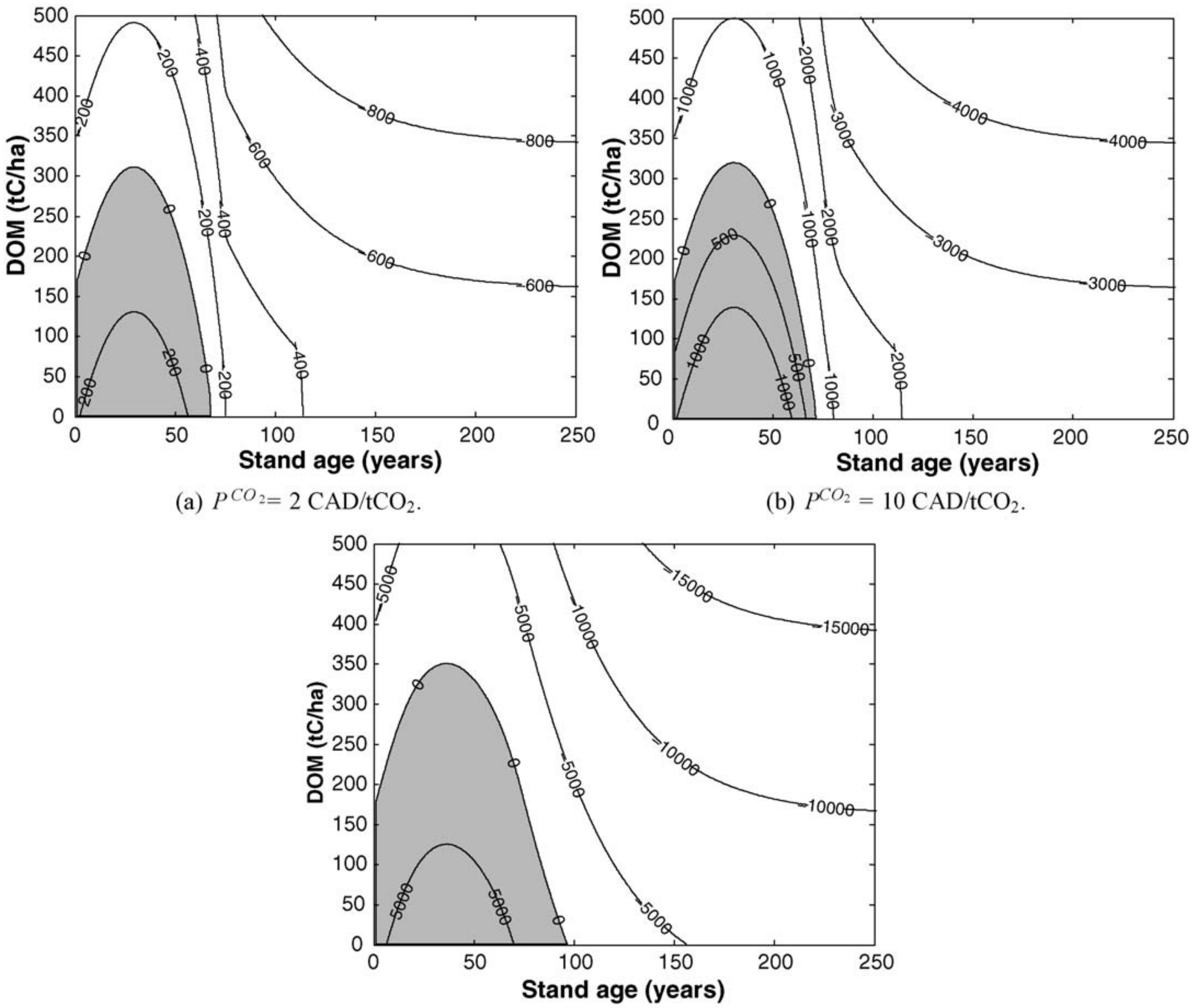


Fig. 5. Land, timber, and carbon values (CAD/ha) by stand age and carbon stocks in the DOM pool for different carbon prices. The contours indicate combinations of age and DOM states that have the same land, timber, and carbon values. The region where LTCV is positive is shaded grey.

Fig. 6 presents the information from Fig. 5 in a manner which highlights the portion of the state space for which participating in the carbon market would be advantageous to the landowner. These contours represent the difference between the LTCVs calculated when $P^{CO_2} = 2$, 10, and 40 CAD/tC and when $P^{CO_2} = 0$. The landowner would find participation in the carbon market to be advantageous when the difference between LTCVs is positive. This occurs when the initial stand is relatively young and has a relatively small DOM pool. The size of the DOM pool where carbon market participation is advantageous is almost always less than the boreal forest average of 340 tC/ha. In other words, given current states of carbon stocks, voluntary participation in the carbon market posited here is unlikely, unless the stand is relatively young with a relatively low stock of carbon in its DOM pool.

In the system we model here, a forest landowner has the choice at each point in time whether to harvest a stand of a particular age and with a particular stock of DOM carbon, or not. In most cases in this system, the tendency will be for increasing carbon prices to result to delay the optimal age of harvest. A benefit to society of the carbon market would be the additional TEC stored in the forest stand and, therefore, not released to the atmosphere. Fig. 7 shows projections of TEC over 1000 years for a stand starting at 50 years of age and 370 tC/ha in DOM stocks under carbon prices of 0 and 10 CAD/tCO_2. The optimal harvest age increases from 73 to 84 years with the 10 CAD/tCO_2 increase in



(a) P^{CO_2}= 2 CAD/tCO$_2$.

(b) P^{CO_2} = 10 CAD/tCO$_2$.

(c) P^{CO_2} = 40 CAD/tCO$_2$.

Fig. 6. Change in land, timber, and carbon values (CAD/ha) from $P^{CO_2} = 0$ case by initial state for different carbon prices. The contour lines indicate combinations of age and DOM that have the same change in LTCV from the $P^{CO_2} = 0$ case. The region of state space where this change is positive shaded grey.

carbon price, so for the 11 years after harvest for the 0 CAD/tCO$_2$ case, there is substantially more TEC carbon in the 10 than the 0 CAD/tCO$_2$ projection. There is no difference between the two projections for the first 23 years between the two cases, because both cases are following the same trajectory up to this point in time. On average, the higher carbon price will have more TEC over the projection period, although due to the asynchronous cycles associated with the different rotation ages, there will be points in time where the zero carbon price case has more TEC. If benefits are measured in terms of the additional amount of carbon stored over a time period, the perceived benefits are quite sensitive to initial conditions and the time period used for evaluation. The sensitivity to length of time period given our starting conditions is illustrated in Table 2.

A major difference between our study and those of van Kooten et al. (1995), Spring et al. (2005a,b), Chladná (2007), and Yoshimoto and Marusak (2007) is that we consider carbon stored in biomass and DOM pools, whereas they ignore biomass pool. In order to evaluate the effect of ignoring the DOM pool, we conducted a series of runs with a modified version of our model where the carbon market considered only biomass carbon. The results are summarized in Table 3 and compared with Table 1. An obvious result is that the optimal harvest decision is independent of DOM stocks when changes in DOM do not affect the objective function. The optimal rotation age and equilibrium carbon

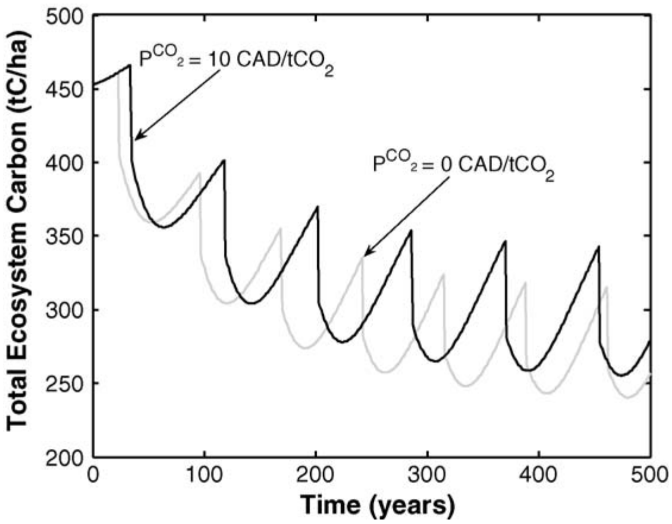


Fig. 7. Projections of total ecosystem carbon stocks for $P^{CO_2} = 0$ and $P^{CO_2} = 10$ CAD/tCO_2 cases given application of the optimal decision rule and an initial stand age of 50 years and initial DOM stocks of 370 tC/ha.

Table 2
Average difference in projection of TEC stocks given optimal policies when $P^{CO_2} = 10$ and $P^{CO_2} = 0$ for different projection periods.

Time (years)	Average difference (tC/ha)
20	0.0
50	20.6
100	8.2
200	18.7
500	17.7
1000	18.8

Table 3
Summary of harvest age and carbon stock and mean annual increment equilibria for different carbon prices when DOM is not considered. The values for $P^{CO_2} = 30$ are the asymptotic equilibria assuming no harvest.

P^{CO_2} (CAD/tCO_2)	Rotation age (years)	DOM and TEC at age 0 (tC/ha)	DOM at rotation (tC/ha)	TEC at rotation (tC/ha)	MAI (m^3/ha/yr)
0	73	257	186	313	3.76
1	75	261	188	317	3.79
2	76	262	189	319	3.80
5	82	272	196	334	3.84
10	94	289	207	362	3.83
20	173	363	265	457	2.79
30	∞	n/a	320	519	0

stocks are greater when the DOM pool is not considered. For carbon prices of 5 CAD/tCO_2 or greater, the differences are substantial. This difference occurs because the amount of CO_2 released to the atmosphere through decomposition is proportional to the stock of carbon in DOM. Maintaining high stocks of DOM is penalized in our approach and is not in the other approaches.

Conclusions

In this study we presented the formulation of, and results from, a dynamic programming model used to determine the optimal harvest decision for a forest stand used to provide both timber harvest volume and carbon sequestration services. The forest stand is described using two state variables: stand age and the stocks of carbon stored in the DOM pool. To the best of our knowledge, this is the first article to examine the impact of varying DOM on the optimal harvest age. This study provides a basic framework for assessing the economic implications of alternative methods of accounting for C stocks in DOM.

We use the model to examine optimal harvest decisions for a lodgepole pine stand in the boreal forest of western Canada. We draw the following main conclusions from our study:

1. The optimal decision is sensitive to current stocks of carbon in the DOM pool, especially when carbon prices are high and initial DOM stocks are low.
2. For many realistic combinations of the initial stand age and DOM carbon stocks, a non-zero carbon price reduced the value of land, timber, and carbon sequestration services relative to the zero case. To some readers, this may be counter-intuitive as the storage of carbon in forests is often considered to be a benefit. However, because of the decomposition of DOM, forest stands can be a net carbon source for several years after stand initiation (Fig. 2). Coupled with a positive discount rate, DOM carbon stocks can represent a significant liability to the landowner, especially if she is required to pay for net carbon emissions in the year that they occur. Because of this, it is quite possible (perhaps even probable) that the economically optimal DOM stocks are smaller than in the initial state (Fig. 4).
3. Compared to the case where changes in carbon stock in only the biomass pool is considered, optimal harvest ages are younger and equilibrium carbon stocks are lower when changes in carbon stocks in the DOM pool are rewarded or penalized.

This article presented the results of an optimal harvesting model for a forest stand where the landowner is paid for net increases in total ecosystem carbon in the stand, and pays for net decreases, on an annual basis. By approximating a detailed carbon budget simulation model using two carbon pools, we were able to develop a dynamic programming model of the system which captures the important elements of the system for an economic analysis. We plan to use variants of this model to explore alternative forms of carbon markets, including one which accounts for carbon pools in forest products.

We demonstrated that the optimal management policy can be substantially different between cases where the market considers and ignores carbon in the DOM pool. This raises an interesting issue because the size of the DOM pool is important from a carbon flux standpoint, but is more difficult to measure than biomass.

We conducted our analysis considering an isolated timber stand, where prices of timber and carbon storage services were determined exogenously. If a large forest area was participating in this market it would change the timber supply and could affect the prices of timber, which would feed back into the optimal harvest decision. The direction of this effect is not clear, as equilibrium timber production (measured by mean annual increment), increased in our example until carbon prices reached about 10 CAD/tCO_2. When carbon prices are high enough, rotation ages lengthen considerably and mean annual increment declines. In these cases, there would be pressure for both higher timber prices and the possibility of increased substitution of building materials such as concrete and steel for wood. We did not examine any effects of this substitution on national or global carbon accounts.

This paper presents a model used for the determination of the optimal harvest age of a single forest stand in the tradition of Faustmann (1849) and Hartman (1976), with the inclusion of a price and a cost associated with the annual sequestration and emission of CO_2. The general results reported here can be expected to differ from forest-level analyses such as those reported by McCarney (2007) and McCarney 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; Spring et al., 2005a,b; Chladná, 2007) because we recognize that a forest stand has both carbon sink (the living biomass) and carbon source (the DOM pool) components. Our results can also be expected to differ from other analyses because of the particular form of the carbon market we assume. 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.

Acknowledgements

The project was supported by the Sustainable Forest Management Network. The initial idea for this study developed out of conversations between Armstrong and his colleagues in the Forestry Project when he was on sabbatical leave at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. We acknowledge the contributions of two anonymous reviewers whose comments greatly improved this article.

References

Aber, J.D., Botkin, D., Melillo, J.M., 1978. Predicting effects of different harvesting regimes on forest floor dynamics in northern hardwoods. Can. J. Forest Res. 8 (3), 306–315.

BC MoFR, 2007. Table interpolation program for stand yields—home. http://www.for.gov.bc.ca/hre/gymodels/Tipsy/index.htm.

BC MoFR, 2009. Market pricing system (MPS) parameters. Historical Interior. http://www.for.gov.bc.ca/hva/parameters_interior.htm.

Bellman, R.E., 1961. Adaptive Control Processes: A Guided Tour. Princeton University Press, Princeton, NJ, USA.

Black, T.A., Harden, J.W., 1995. Effect of timber harvest on soil carbon storage at blodgett experimental forest, California. Can. J. Forest Res. 25 (8), 1385–1396.

CCX, 2009. CCX CFI market data charting tool. http://www.chicagoclimatex.com/market/data/summary.jsf (Accessed 23.06.09).

Chladná, Z., 2007. Determination of optimal rotation period under stochastic wood and carbon prices. For. Pol. Econ. 9 (8), 1031–1045, doi:10.1016/j.forpol.2006.09.005.

Covington, W.W., 1981. Changes in forest floor organic-matter and nutrient content following clear cutting in northern hardwoods. Ecology 62 (1), 41–48.

Davis, L.S., Johnson, K.N., Bettinger, P., Howard, T.E., 2001. Forest Management: To Sustain Ecological, Economic, and Social Values. McGraw-Hill, Dubuque, IA, USA.

Faustmann, M., 1849. Calculation of the value which forest land and immature stands possess for forestry. J. Forest Econ. 1, 7–44, reprinted in 1995.

Gutrich, J., Howarth, R.B., 2007. Carbon sequestration and the optimal management of New Hampshire timber stands. Ecol. Econ. 62 (3–4), 441–450, doi:10.1016/j.ecolecon.2006.07.005.

Hartman, R., 1976. The harvesting decision when a standing forest has value. Econ. Inq. 14, 52–58.

IPCC, 2000. Land use, Land-use Change, and Forestry. Cambridge University Press. Cambridge UK. Also available at http://www.ipcc.ch/ipccreports/sres/land_use/.

IPCC, 2006. Guidelines for National Greenhouse Gas Inventories. IGES, Hayama, Japan, prepared by the National Greenhouse Gas Inventories Programme. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Jessome, A.P., 1977. Strength and related properties of woods grown in canada. Forestry Tech. Report no. 21, Eastern Forest Products Laboratory, Ottawa, Canada.

Kaipainen, T., Liski, J., Pussinen, A., Karjalainen, T., 2004. Managing carbon sinks by changing rotation length in European forests. Environ. Sci. Policy 7 (3), 205–219, doi:10.1016/j.envsci.2004.03.001.

Kull, S.J., Kurz, W.A., Rampley, G.J., Banfield, G.E., Schivatcheva, R.K., Apps, M.J., 2007. Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.0: User's Guide. Natural Resources Canada. Canadian Forest Service. Northern Forestry Centre, Edmonton, Canada. http://nofc.cfs.nrcan.gc.ca/bookstore_pdfs/28106.pdf.

Kurz, W.A., Apps, M.J., Webb, T.M., MacNamee, P.J., 1992. The carbon budget of the Canadian forest sector: Phase 1. Inf. Rep. NOR-X-326, Forestry Canada. Northern Forestry Centre, Edmonton, Canada.

McCarney, G.R., 2007. Management decisions in the boreal forest considering timber and carbon market incentives. Master's thesis, Department of Rural Economy. University of Alberta, Edmonton, Canada.

McCarney, G.R., Armstrong, G.W., Adamowicz, W.L., 2008. Joint production of timber, carbon, and wildlife habitat in the Canadian boreal plains. Can. J. Forest Res. 38, 1478–1492, doi:10.1139/X07-246.

Point Carbon, 2009. Historic prices—Point Carbon. http://www.pointcarbon.com/news/historicprices/.

Pratap, R., 2006. Getting Started with MATLAB 7: A Quick Introduction for Scientists and Engineers. Oxford University Press, New York, NY, USA.

Samuelson, P.A., 1976. Economics of forestry in an evolving society. Econ. Inq. 14, 466–492.

Spring, D., Kennedy, J., Mac Nally, R., 2005a. Optimal management of a flammable forest providing timber and carbon sequestration benefits: an Australian case study. Aus. J. Agric. Res. Econ. 49 (3), 303–320.

Spring, D.A., Kennedy, J.O.S., Mac Nally, R., 2005b. Optimal management of a forested catchment providing timber and carbon sequestration benefits: climate change effects. Global Environ. Change 15 (3), 281–292, doi:10.1016/j.gloenvcha.2005.04.002.

van Kooten, G.C., Binkley, C.S., Delcourt, G., 1995. Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. Am. J. Agric. Econ. 77 (2), 365–374.

Yoshimoto, A., Marusak, R., 2007. Evaluation of carbon sequestration and thinning regimes within the optimization framework for forest stand management. Eur. J. Forest Res. 126 (2), 315–329, doi:10.1007/s10342-006-0150-6.