

Effects of Partial Harvest on the Carbon Stores in Douglas-fir/Western Hemlock Forests: A Simulation Study

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ABSTRACT

The STANDCARB 2.0 model was used to examine the effects of partial harvest of trees within stands on forest-related carbon (C) stores in a typical Pacific Northwest *Pseudotsuga/Tsuga* forest. For harvest rotation intervals of 20 to 250 years the effect of completely dispersed (that is, a checker-board) versus completely aggregated cutting patterns (that is, single blocks) was compared. The simulations indicated that forests with frequent, but partial removal of live trees can store as much C as those with complete tree harvest on less frequent intervals. Stores in forest products generally declined as the fraction of live trees harvested declined and as the interval between harvests increased. Although the proportion of total system stores in forest products increased as

the frequency of harvests and proportion of trees removed increased, this did not offset the reduction in forest C stores these treatments caused. Spatial arrangement of harvest influenced tree species composition profoundly; however, the effects of aggregated versus dispersed cutting patterns on C stores were relatively small compared to the other treatments. This study indicates that there are multiple methods to increase C stores in the forest sector including either increasing the time between harvests or reducing the fraction of trees harvested during each harvest.

Key words: carbon sequestration; carbon management and dynamics; disturbance; forest products; simulation modeling; Pacific Northwest.

INTRODUCTION

Forests are a critical part of the biological carbon (C) cycle and their management may contribute to stabilizing the concentration of the greenhouse gas C dioxide in the atmosphere (Pacala and Socolow

2004). Forests have great potential to store C (Post and others 1990; Dixon and others 1994), but the degree to which this potential is being met is uncertain. Clearing forests for agriculture and other land uses (Houghton and others 1983; Hall and Uhlig 1991), harvesting for commercial forest products (Cooper 1983; Houghton and others 1983; Harmon and others 1990), and the removal of non-commercial products such as fuel wood (Brown and others 1991; Houghton 1991) have decreased the amount of C stored in forests. Conversely, afforestation, fertilization, and protection from fire and insects have increased the amount of C stored

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by forests (Tans and others 1990; Kauppi and others 1992; Cias and others 1995; Pacala and others 2001). Globally, forests are a net sink of C from the atmosphere (Gurney and others 2002), although very little of this current sink is due to actions directly related to deliberate C sequestration policies. If forests are to be deliberately managed to sequester additional C then the impact of various management approaches needs to be better understood.

Although timber harvest has generally reduced global terrestrial stores of C, the local effect of this activity is highly dependent on the initial conditions. Conversion of older forest to younger forests has generally been shown to release C to the atmosphere (Cooper 1983; Cropper and Ewel 1987; Harmon and others 1990; Dewar 1991; Schulze and others 2000; Harmon and Marks 2002). On the other hand, the creation of plantations on non-forest lands will generally increase C stores even when harvest occurs (Kauppi and others 1992; Kershaw and others 1993; Sedjo and Solomon 1991; Richter and others 1999; Johnsen and others 2001). Simply put, the net effect of harvest is dependent on whether the average C store in the initial condition is larger or smaller than the average C store in the harvested system (Harmon 2001).

The amount of C stored in a landscape is influenced by the interval between harvests and the fraction of C removed by disturbances. In general, the longer the interval between disturbance and less effective the disturbance is in removing C, the greater the average C store there is in a forested landscape (Smithwick and others 2007). A common result of most simulation studies is that as the interval between disturbances increases, the average C store in the system increases (Dewar 1991; Dewar and Cannell 1992; Harmon and Marks 2002). Thus, when timber harvest shortens the interval between disturbances a decline in average forest C stores can be expected. However, when a timber harvest system protects a forest from a more frequent disturbance (for example, fire) the average C store can increase with harvest (Kurz and others 1998; Seely and others 2002). Less clear is the effect of disturbances in removing C, in part, because during harvest, some of the removed C is stored offsite in forest products. In the case of site preparation practices, the more C removed in fires the lower the amount of C stored (Harmon and Marks 2002). Wildfires generally remove far less onsite C from forests than timber harvest (Tinker and Knight 2000), although as stated above some fraction of the harvest removal is stored offsite.

Typically 30-50% of the harvested C is lost in manufacturing and initial use, a loss that is larger than could be expected from even the most extreme forest fire (Harmon and others 1996; Tinker and Knight 2000; Campbell and others 2008).

Partial harvest of trees within a forest stand may also store more C than complete harvest (Dewar and Cannell 1992; Thornley and Cannell 2000), but there are uncertainties concerning the realism of these simulation studies. This is because most simulation models do not assess the impact of harvest pattern on foliage regrowth. Minimal impact of harvest pattern within a stand is likely in two cases: (1) complete removal of the trees, and (2) minor removals (for example, <2% per year). In the first case, there are no remnant trees to affect foliage development, whereas in the second case foliage losses can be replaced by minor amounts of growth. However, in the case of partial harvest the situation is potentially more complicated. Given that trees have a maximum crown width, there are levels of foliage removal that cannot be replaced by horizontal regrowth of existing trees. Replacing foliage in this situation depends on establishment and regrowth from below the canopy. This means that the remaining trees can influence the rate of foliage recovery by reducing light reaching the regenerating trees. Moreover, because the remaining trees affect light levels in the understory this can lead to changes in species composition, which can also influence C stores.

In this article, the STANDCARB model is used to examine the effects of partial harvest for forest stands on the dynamics of C in a hypothetical forest stand (Harmon and Marks 2002; Smithwick and others 2003). STANDCARB is a suitable choice to examine this aspect of forest management because it was designed to overcome common ecosystem model restrictions by incorporating the features of a gap simulation model (Urban and Shugart 1992) with an ecosystem process model (Harmon and others 1990). In STANDCARB, trees are simulated in a spatially explicit grid work and are assumed to have a maximum crown diameter with taller trees influencing the light environment of underlying and adjacent trees. Moreover, multiple tree species can exist in a stand with their abundance determined by their light environment. Given that tree species can also have different C-related parameters (for example, decomposition rates), it is therefore possible for changing species composition to change C dynamics. These features allow a more realistic examination of more complicated scenarios such as partial harvest within a stand. Our specific objective was to examine the effect of partial harvest of

live tree C on forest-related C stores. We examined a range of intervals between harvests and considered the C stores within the forest itself as well as in the forest products derived from timber harvest. We also examined the effect of cutting patterns by contrasting completely dispersed (that is, a checkerboard) versus completely aggregated patterns (that is, contiguous blocks).

MATERIALS AND METHODS

STANDCARB Model Overview

General aspects of STANDCARB are described by Harmon and Marks (2002) and Smithwick and others (2003). Detailed documentation of the model including example input and output files is available from <http://andrewsforest.oregonstate.edu/liter/pubs/webdocs/models/standcarb2.htm>. Below we review general aspects of the model and modifications of version 2.0.

STANDCARB simulates the accumulation of C over succession in mixed-species and mixed-aged forest stands. The model is parameterized for stands in the Pacific Northwest and as in many other C models it does not include the effects of nutrient cycling. This means that we assume that nutrient stores will not be influenced by the treatments enough to lead to major changes in site productivity. STANDCARB uses difference equations on an annual time step for all variables, except those

used to estimate the effects of climate on tree establishment, growth, and decomposition. These climate-related variables are calculated on a monthly time step. Spatially, STANDCARB is designed to simulate the dynamics of a number of cells within a stand. Each cell represents the area occupied by a single, mature tree (in these particular simulations this is an area of approximately 0.04 ha), although, depending on age, a cell can represent either a cohort of trees or a single tree. Within a cell spatial arrangement of trees is not considered; however, the relative height of trees in a cell determines the degree of interaction among cells.

STANDCARB uses a number of levels of organization to estimate changes in C stores within a stand (Figure 1). A stand is comprised of a number of *cells*, each of which contains up to four *layers* of vegetation, seven detritus pools, and three stable (that is, soil, wood, and foliage) pools. Four layers of vegetation can occur in each cell: (1) upper trees, (2) lower trees, (3) shrubs, and (4) herbs. There is only one species in the upper and lower trees in each cell; these can be the same or different species. Each of the layers can potentially have seven live *parts*: (1) foliage, (2) fine roots, (3) branches, (4) sapwood, (5) heartwood, (6) heart-rot, and (7) coarse roots. Each of the live parts of each layer contributes material to corresponding detritus or dead *pools* with the exception that heartwood and

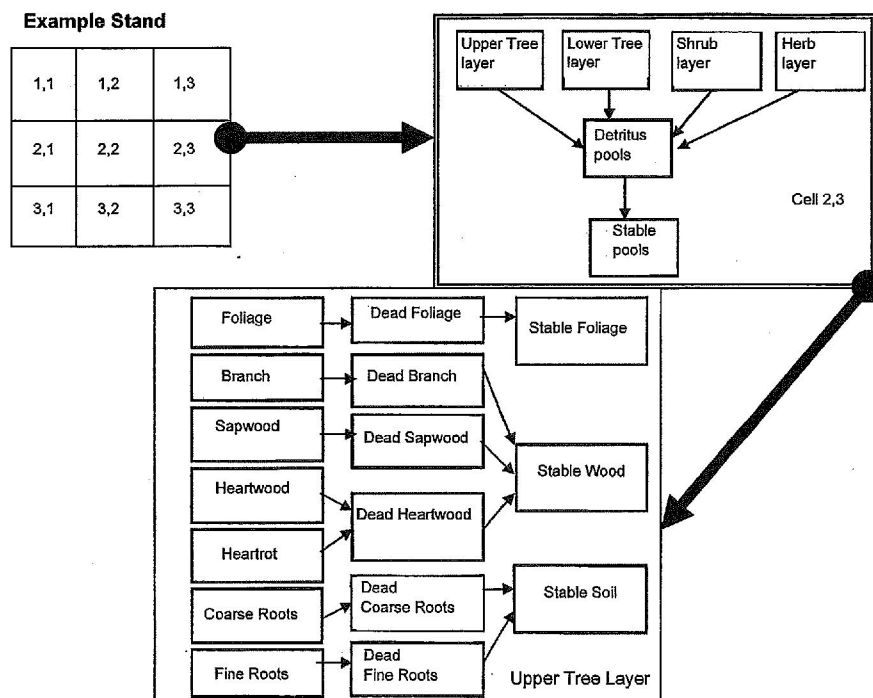


Figure 1. Conceptual structure of STANDCARB model showing the relationship among the stand, cells, plant layers, layer parts, detritus, and stable pools.

heart-rot contribute to the dead heartwood pool. Finally, all the detritus pools in a cell add material to either stable foliage, stable wood, or stable soil pool. Although stable pools lose C, their dynamics are much slower than that of the dead pools; stable pools thus represent highly decomposed materials.

Changes in STANDCARB 2.0

As with the original version, STANDCARB 2.0 contains 11 major modules that perform specific functions (Figure 2). The following section describes the modifications relative to version 1.0 of the model (Harmon and Marks 2002).

1. The time a cell takes to switch from a cohort to a single upper tree is now determined stochastically once the minimum age has been reached, whereas in version 1.0 the switch occurred once this minimum was reached.
2. The maximum tree height is now a function of site index.
3. The light coming into a cell is reduced by shading from surrounding cells, whereas in version 2.0 a small proportion of direct light is allowed to pass through neighboring cells to account for the sun flecks passing through minor openings.
4. The productivity of the trees in version 2.0 changes with age, so that as trees reach their maximum height their production declines by an amount set by the user. This accounts for the fact that production in older forests appears to be limited relative to younger forests (Acker and others 2000, 2002). Although there is some dispute about the exact cause of this phenomenon, there is little doubt it occurs in many types

of forests (Ryan and others 1997).

5. Heart-rot is now formed from heartwood after trees reach a minimum age, although the year heart-rot begins to form in a particular cell is stochastic.
6. Dead sapwood and dead heartwood are now separated into standing and downed material to account for the different microclimates of these two positions.
7. Dead pools are now tracked using a cohort structure for each year's input for a cell to account for the fact that a period of decomposition is required before stable materials are formed. Once a lag time, which is modified by climatic conditions, has been exceeded a dead pool cohort is stochastically transferred to the appropriate stable pool.
8. There are now three "stable" pools instead of one. Dead foliage is transferred to stable foliage (that is, the organic horizon), aboveground dead wood pools to stable wood, and dead fine and coarse roots to stable soil.

Model Calibration

Given that the purpose of our simulation experiments was to predict the relative effects of partial harvest on potential C stores, we calibrated STANDCARB to represent a common mixed-species forest in the Pacific Northwest. We therefore make no claims that the absolute levels of C stores are being predicted *a priori*. The simulated stands represent a mixture of two species, each with different potentials to store C (Table 1). The model determines how the mixture of species changes over succession, with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) dominating early and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) dominating later in succession. The parameters of these species (Supplementary Table 1) are based on values estimated for Douglas-fir and western hemlock, with the latter storing approximately 6% less C on average (Mg ha^{-1}) than the former (Table 1). Therefore a species with higher potential is eventually replaced by one with lower C stores potential.

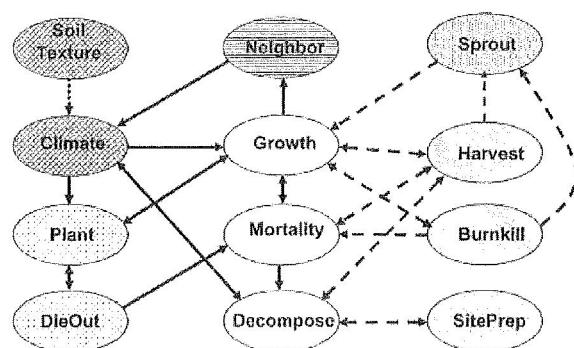


Figure 2. Major modules in STANDCARB model. Crosshatching indicates modules controlling driving variables; stippled population processes; horizontal lines cell to cell interactions; open ecosystem processes; and shaded disturbance processes.

Table 1. Model Predictions of Steady-State C Stores (Mg C ha^{-1}) of Each of the Two Species as well as the Mixed Forest Used in the Simulations

Species	Live	Dead	Stable	Total
Western hemlock	311	147	98	556
Douglas-fir	320	139	109	568
Mixed forest	323	151	102	578

Table 2. Character of the Site Used in the Simulations in Terms of Climate, Radiation, and Soil

Variable	Value
Mean annual temperature	8.6°C
Minimum monthly temperature	-1.5°C
Maximum monthly temperature	18.3°C
Mean annual precipitation	230 cm
Mean monthly diffuse radiation	157 cal cm ⁻² day ⁻¹
Mean monthly direct radiation	186 cal cm ⁻² day ⁻¹
Soil/rooting depth	100 cm
Soil texture	Loam
Coarse fragments (> 2 mm)	None

We also assumed that wood-related production would decline 40% when trees reached their maximal height, a value consistent with observations (Acker and others 2000, 2002).

The climate and radiation data used to drive the simulations were from the H. J. Andrews Experimental Forest, a typical Oregon Cascade site (Table 2). The soil was a loam, with no coarse fragments larger than 2 mm in diameter, and a depth of 1 m. Live biomass accumulation rates of the species were calibrated to match those predicted from yield tables (McArdle and Meyer 1930; Barnes 1962) for productive sites (Site Class 3). Stores in detritus and soils were calibrated to older published data (Grier and Logan 1977), but also match those of other more recent studies of forests that had been disturbed catastrophically by fire 400 to 500 years ago (Harmon and others 2004; Smithwick and others 2002).

Forest Products Stores

Although our primary purpose in these simulation experiments is to examine the potential effect of various practices on C stores in forests, C is stored in forest products following timber harvest. Therefore, we examined two contrasting cases: (1) maximal and (2) minimal storage in long-term products. The former, termed the high storage system was simulated by assuming that 75% of the harvest would be converted to a mix of various long-term forest products that lost C at an average rate of 0.01 y⁻¹. The latter, termed the low storage system, was simulated by assuming 50% of the harvest would be converted to long-term forest products that lost C at an average rate of 0.02 y⁻¹. We assumed that manufacturing efficiencies would not change over the course of the simulations.

Simulation Experiments

For each of the simulation experiments there were five replications of each treatment and these were

averaged for analysis. We used a 20 x 20 grid for these simulations, which given the size of our cells would represent a stand of approximately 11.5 ha. We assumed that the height of trees in the cells surrounding the simulation cells was the average of the cells within the simulation. We assumed that trees would fully stock the stand within 5 years, the legal requirement under the state of Oregon's Forest Practices regulations. Except in the case of the first experiment without major disturbances, we allowed the model to run 500 years before disturbance was introduced. To estimate the mean C stored by the particular system, we averaged the C in each aggregate pool being considered (live, dead, stable, ecosystem total, forest products, and total system) over a series of rotations once the values oscillated about a long-term average (that is, a stationary time series in which the starting and ending points of each cycle are the same). The time required to reach a stationary time series increased with the interval between harvests; we ran simulations until at least three stationary cycles were reached and we averaged at least three cycles to reduce the effects of minor variations caused by the stochastic nature of the model. Although a long simulation time was required to produce a stationary time series, the purpose was not to project changes in C stores thousands of years in the future; rather the intent was to calculate a representative average C store. Given the different light requirements of the two species we examined, it is likely that harvesting different amounts and in different patterns would result in different species mixtures. We therefore also calculated the minimum, maximum, and average proportion of tree biomass that was comprised of Douglas-fir.

In the first experiment we allowed the simulation to proceed for 2000 years without a major disturbance. Although this situation would be extremely rare in nature, it allowed us to see how the model would respond over the long-term.

In a second and main set of experiments, we examined the effect of partial cutting in a series of simulations in which live trees in 20, 40, 60, 80, or 100% of the cells had all the stem-related pools cut. This is quite different than in most models, because in those a fraction of the live C is removed over the entire area. Although our treatment had a similar effect, the remaining live mass had an influence on the growth of the next generation of forest through shading, which can have a significant effect on C stores (Smithwick and others 2003). This also altered the microclimate for the dead and stable pools. For all these simulations, we assumed that harvests did not involve the removal of any dead

material and that 95% of the stem-related pools that were cut were removed. We also examined the arrangement of harvest patterns. In a preliminary test (not reported here), we examined the effect of harvesting 20% of the cells over a range of rotation intervals. This indicated a continuous change as we proceeded from 1, 2, 4, 8, and 80 separate harvest blocks out of a possible 400. We therefore contrasted a totally aggregated harvest pattern (contiguous blocks) with a totally dispersed pattern (single cells in a checkerboard of harvest-no harvest) within a stand. Note that our simulations affected all the live trees in the cells being harvested and none of the trees in cells that were not harvested. For each amount of harvest and pattern, we examined harvest rotation intervals of 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, and 250 years.

RESULTS

Experiment 1: No Major Disturbance Simulation

When major disturbances were excluded, the amount of C in all aggregate pools except the stable pool increased for the first 200-300 years (Figure 3). The aggregate stable pool initially decreased because of the temporal lag in the formation of this form of C. After reaching a peak in C stores, all the C pools declined to a long-term steady-state store after 600-700 years of age. The cause of this decline was related to the live pool dynamics; decreases in that pool limited the stores in the dead and stable pools. The decrease in live pools was caused in part by the decline in woody part production related to tree height/age and the appearance of heart-rots in the older trees. The cause of the mid-successional peak in C stores was mostly likely due to the lower light compensation point of

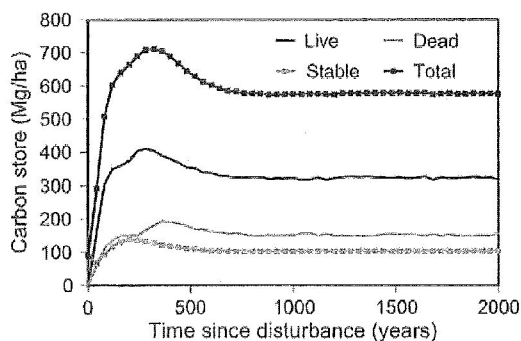


Figure 3. Live, dead, stable, and total C stores for mixed Douglas-fir/western hemlock forest without major disturbance.

western hemlock which allows more overall C uptake by living trees; both Douglas-fir and western hemlock were present in intermediate stand ages. When these species were run separately this peak in live and dead C was not evident. The steady-state averages of the pools also indicated that the mixed-species forest could store slightly more C than a single species forest (Table 1).

Experiment 2: Partial Cutting Simulations

For both the aggregated and the dispersed cutting pattern within a stand, the average amount of live C increased as the interval between disturbances increased (Figure 4). In general, the less live C that was harvested, the larger the average live C store. These differences were greatest for the shortest intervals between harvests, with a 20% harvest system containing 5.5 to 6 times the average live C of a 100% harvest system. For aggregated cutting patterns, partial cutting stored more live than 100% harvest for all the rotation intervals examined; however, for the dispersed cutting pattern the 100% harvest started to store more than some of

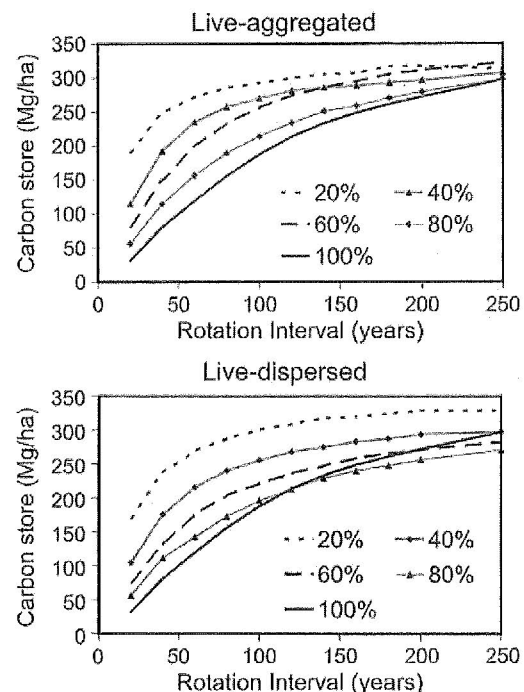


Figure 4. Average live C stores over a harvest rotation interval for different levels of removal (percent of cells harvested) and cutting patterns. Aggregated represents one contiguous harvest block and dispersed represents a checkerboard pattern of harvest-no harvest.

the partial dispersed cutting patterns when the interval between harvests exceeded 100 years. The causes of these patterns were several-fold. First, by leaving live C in the forest at all times, partial harvests increased the overall average. Second, as the length of the interval between harvests increased, the differences in heights between the harvested and non-harvested cells also increased. With a dispersed cutting pattern the tallest trees were adjacent to the smallest trees and therefore the limitations due to shading were highest. Although these interactions occurred in aggregated cutting patterns, there were also cases in which small trees were next to small trees and tall ones next to tall ones. This meant that the height difference between harvested and non-harvested cells was less important and may explain why the live C stores for partial harvests with 40-60% live tree removals converged after 125 years. For the 100% cut, these differences in height among cells were minimal, so that at very long intervals of harvest there were more trees with optimal lighting.

Average dead C stores were higher for the aggregated cutting patterns, but the basic trends were quite similar to the dispersed cutting patterns (Figure 5). Unlike the case for live C, there did not

seem to be an interaction between the pattern of cutting and the amount cut, with higher levels of harvest leading to lower average dead C stores. The difference between the 20 and 100% harvest was largest for the shortest interval between harvests; for a 20-year interval the 20% harvest had 1.7 times the average dead store of the 100% harvest.

The stable C store seemed the most sensitive of all the pools in terms of cutting patterns, with aggregated patterns generally storing more on average than dispersed patterns (Figure 6). In the case of the aggregated pattern, the harvest rotation interval that produced the maximal average stable C store was between 20 and 100 years, with the rotation interval needed to reach the maximum increasing as the proportion harvested increased. In the case of the dispersed patterns, there were also maxima, but these appeared to generally occur at rotation intervals of less than 40 years. There are several possible causes for the differences between the two partial cutting patterns, but the most likely is the differences in live C between the two patterns. Live C generally was higher for the aggregated patterns. It was also likely that the environment for decomposition was altered, with

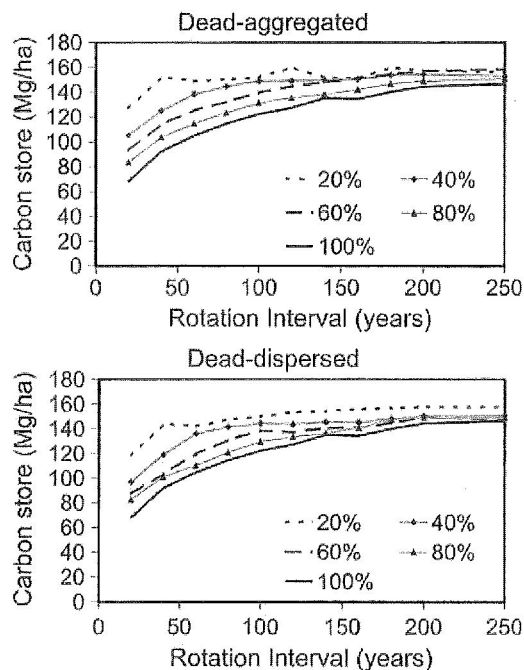


Figure 5. Average dead C stores over a harvest rotation interval for different levels of removal (percent of cells harvested) and cutting patterns. Aggregated represents one contiguous harvest block and dispersed represents a checkerboard pattern of harvest-no harvest.

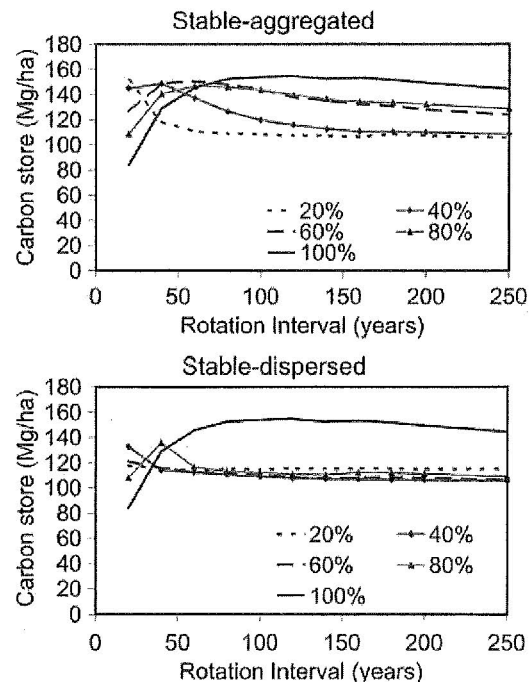


Figure 6. Average stable or soil C stores over a harvest rotation interval for different levels of removal (percent of cells harvested) and cutting patterns. Aggregated represents one contiguous harvest block and dispersed represents a checkerboard pattern of harvest-no harvest.

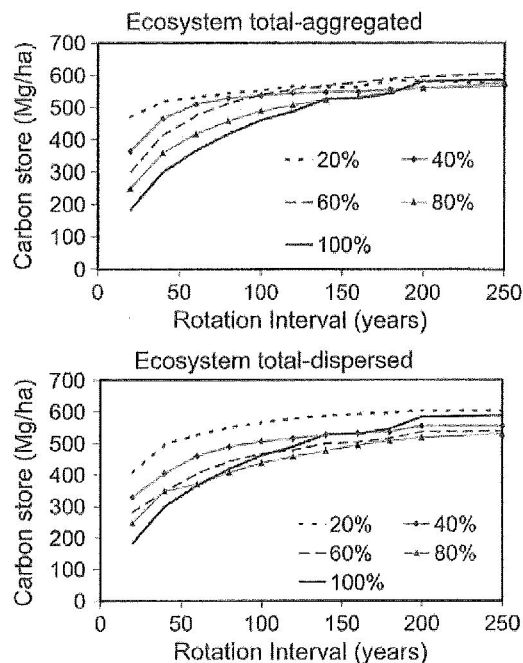


Figure 7. Average total ecosystem C stores over a harvest rotation interval for different levels of removal (percent of cells harvested) and cutting patterns. Aggregated represents one contiguous harvest block and dispersed represents a checkerboard pattern of harvest-no harvest.

the dispersed cutting having a more favorable environment for decomposition.

The average ecosystem total C increased with the interval between harvests (Figure 7). As with live C there was an interaction between the proportion of cells harvested and the pattern of harvest. In the case of aggregated cutting patterns, the lower the proportion of cells harvested, the more C stored in the system on average at least up to a rotation interval of 150 years. These differences decreased as the interval between disturbances increased and in the case of a 20-year harvest rotation the 20% harvest stored 2.2 times more than the 100% harvest. Once the rotation interval exceeded 200 years there were minor differences between the amounts harvested. For the dispersed cutting patterns, the 100% harvest began to surpass the C amounts in some of the partial harvest systems once the interval exceeded 60 years, and after intervals of 180 years and longer the 100% harvest exceeded all but the 20% harvest system. The difference between the aggregated and dispersed patterns was largely due to the response of the live and stable C pools.

The shape of the response of average C stored in forest products to rotation interval was similar regardless for the pattern of harvest or the forest

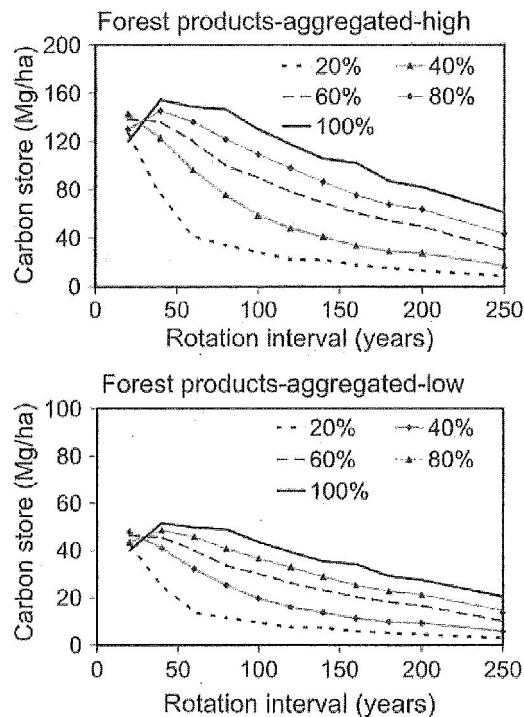


Figure 8. Average forest products stores over a harvest rotation interval for different levels of removal (percent of cells harvested) for the aggregated cutting pattern. Low represents a system in which 50% of the harvested C is converted to long-term forest products with losses of 2% per year; high represents a system in which 75% is converted to long-term forest products with losses of 1% per year. Results for the dispersed cutting pattern were nearly identical.

product storage system examined (Figure 8). As expected, converting more harvest into forest products that lasted longer lead to a larger average C store (that is, approximately a threefold difference) than the converse. Changing the proportion harvested lead to a complex response, with the different proportions having different times to yield the maximal forest products store. In general, the rotation interval to store the maximal amount of forest products increased as the proportion of harvest increased. Specifically, the interval to produce a maximum for the 20 and 40% harvest appeared to be less than 20 years, for 60% harvest it appeared to be 20 years, and for 80 and 100% harvest it appeared to be 40-50 years. Once the maximum was reached, the average store in forest products declined gradually for all the cases except the 20% harvest, which declined very sharply for rotation intervals between of 20 and 60 years. Several factors contributed to the patterns simulated. On one hand, as the forests aged there was more live C to

Table 3. Average Mass of Live C Removed Each Harvest (Mg C ha^{-1} per Harvest) for Different Proportions of Live Harvest, Rotation Intervals, and Cutting Patterns (Aggregated Versus Dispersed)

Rotation interval (years)	Proportion of live stem harvested (%)								
	Aggregated					Dispersed			
	20	40	60	80	100	20	40	60	80
20	35	32	39	36	33	35	40	39	35
40	41	53	74	78	83	40	69	78	77
60	33	77	95	109	121	33	76	99	111
80	36	79	109	130	151	35	77	107	131
100	35	81	119	146	173	35	74	114	143
120	35	77	126	155	188	34	75	116	147
140	36	72	126	157	197	34	69	104	148
160	36	70	127	158	203	35	68	104	149
180	36	70	131	163	208	34	69	107	151
200	34	73	132	168	217	34	69	111	157
250	35	70	126	175	245	35	67	106	145

harvest, and in this set of simulations this would have occurred until a forest age of at least 300 years (Figure 3). Therefore increasing the interval between harvests increased the amount harvested each time (Table 3). On the other hand, increasing the interval between harvests increased the time forest products were lost without replacement and tended to reduce the average amount harvested per year. This lowered the average C store in the forest products pool. Reducing the proportion of cells harvested effectively reduced the amount harvested, but this was countered by the fact, at least for very short rotations, that those trees that were not harvested become larger by the time of the next harvest. Eventually, this effect of increasing the

average size of trees was negligible. For a 100% harvest system, all the trees were generally the same size, and the maximum tree size was reached at a longer interval between harvests.

The response of the average system total C differed with the degree of aggregation in the cutting pattern (Figure 9). For all the management systems examined, there was an increase in average system C stores as the interval between harvests increased. The addition of forest products narrowed the difference between the partial and complete harvests. In the case of the low forest products storage system, these increases were not enough to counter decreases in ecosystem C stores. In the case of the high forest products storage system, these increases

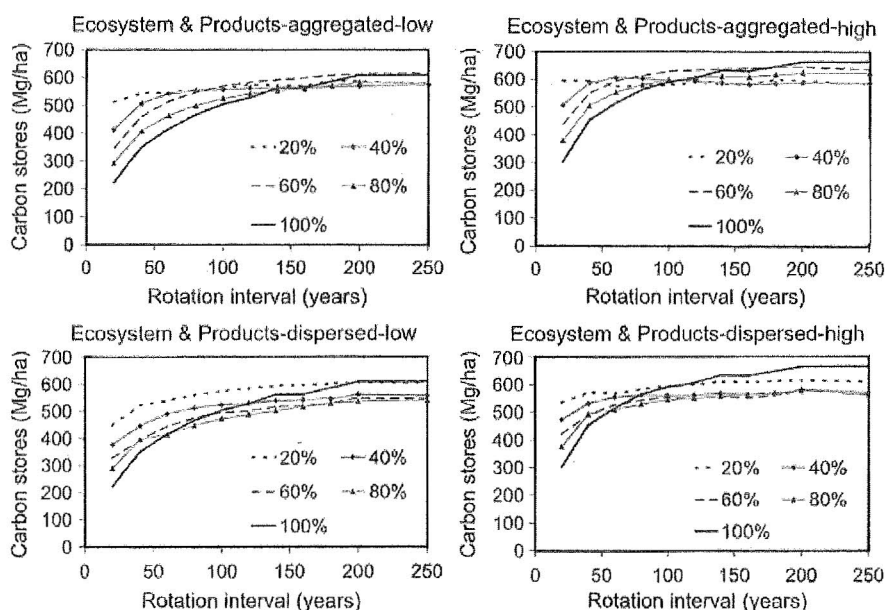


Figure 9. Average total system (ecosystem and forest products) C stores over a harvest rotation interval for different levels of removal (percent of cells harvested) and cutting patterns. Aggregated represents one contiguous harvest block and dispersed represents a checkerboard pattern of harvest-no harvest. Low represents a system in which 50% of the harvested C is converted to long-term forest products with losses of 2% per year; high represents a system in which 75% is converted to long-term forest products with losses of 1% per year.

were enough to counter decreases in ecosystem C stores for the 100% harvest system once the rotation interval exceeded 125–175 years. At the shortest intervals between harvests the 20% harvest stored approximately two times more than the 100% harvest systems. For the aggregated harvest patterns, average total systems stores became very similar once rotation intervals exceeded 160 years, although it should be noted that the stores in the 100% harvest high forest products storage system continued to increase. For the dispersed harvest patterns, harvesting a lower proportion of cells resulted in more C stored in the system for short rotation intervals. However, in comparison to 100% harvest, dispersed patterns of harvest began to store less C once the interval exceeded 60 years, and at an interval of 200 years the 100% harvest generally stored more.

The amount and pattern of harvest had major effects on tree species composition (Figure 10). In the case of complete harvest (that is, 100%),

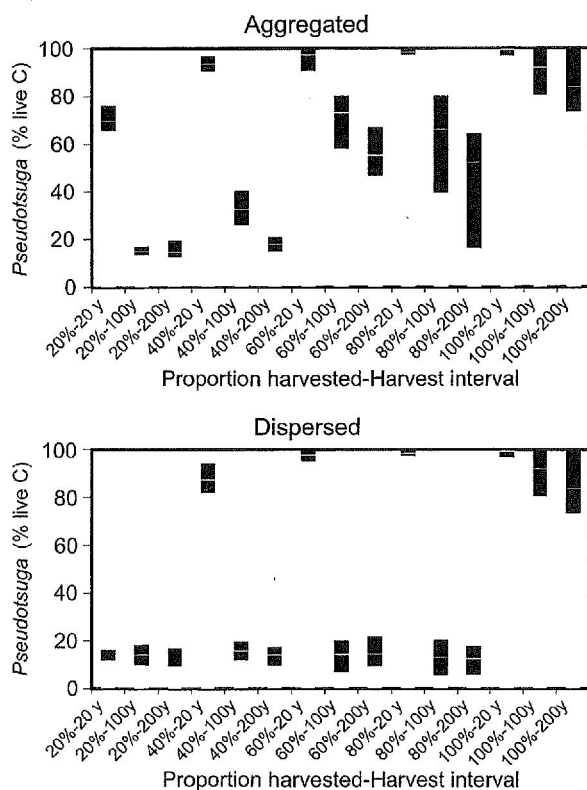


Figure 10. Proportion of the stand live C comprised of Douglas-fir (*P. menziesii*) for different levels of removal (percent of cells harvested) and cutting patterns. The bars represent the range and the white line represents the average over a rotation interval. Aggregated represents one contiguous harvest block and dispersed represents a checkerboard pattern of harvest–no harvest.

Douglas-fir remained the dominant tree species for rotation intervals from 20 to 200 years. For partial harvests, there were three trends: (1) as the proportion of cells harvested increased, the proportion of Douglas-fir increased; (2) as the interval between harvests increased, the proportion of Douglas-fir decreased; and (3) aggregated patterns of harvest lead to higher amounts of Douglas-fir than dispersed ones. Perhaps the most dramatic example of the latter was for 20% harvest with a 20-year rotation interval. When the harvest pattern was aggregated Douglas-fir comprised 70% of the live tree C. However, for a dispersed harvest pattern with the same amount and interval of harvest, Douglas-fir averaged 12% of the live tree C. In fact there were few combinations of harvest amount and interval that lead to Douglas-fir comprising more than 30% of the live C at any time between harvests when the dispersed harvest system was used.

DISCUSSION

Our simulation experiments examined the effects of rotation length and proportion of trees harvested on forest C stores. Our results match those of an earlier study using STANDCARB (Harmon and Marks 2002), but here we more thoroughly examined the effects of partial harvest and the interactions of trees of different ages. The current experiments show that partial harvest of live trees may lead to higher C stores than complete harvest, especially when the interval between harvests is short. We found that arrangement of the partial harvests employed within a stand (that is, aggregated versus dispersed) had a major effect on species composition, but had smaller effects on C stores than the proportion removed or the rotation interval.

Given that our model included the effect of remnant trees on the rest of the system, it would appear that the presence of live trees does not reduce net primary production (NPP) or increase decomposition enough to overcome the effect of leaving more live C in the forest throughout the rotation. Partial harvesting can damage remaining trees and increase their mortality rates for several years (Beese and Bryant 1999). Our model did not consider these effects and although inclusion of them would have made the model more realistic, it is unlikely that they would have been large enough to alter the general conclusions. For example, there was at least a twofold difference between a 20% versus a 100% harvest system when a 20-year interval harvest was used. NPP of the surviving trees would have to be permanently reduced two-

fold for these two systems to store the same amount of C. Beese and Bryant (1999) report that 5-25 % of the remaining trees died within a 3-year period when 95% of the tree volume was harvested, but these tended to be the intermediate crown class indicating less biomass would have been lost. Our simulations were probably more similar to the patch cuts examined by Beese and Bryant (1999) which had a 3-year cumulative mortality of 1%, a value less than that used for the annual mortality in our simulations.

Our model did not include nutrient cycling and this probably influenced the impact of short rotations on C stores. Our results would be representative as long as the site preparation treatments and harvest rotation intervals do not change the overall nutrient availability of the forest. Given the fact only tree stems were removed in our simulations, nutrient status should not have declined greatly. However, the results of others (for example, Seely and others 2002) indicate that for short rotations there could be a 10% drop in C stores associated with nutrient limitations. Thus the differences we estimated between short and longer rotations as well as partial versus complete tree stem harvest are likely to be conservative.

Our result that increasing rotation length increases forest C stores has been found in numerous studies. In Finland, both Liski and others (2001) and Pussinen and others (2002) found that longer rotation lengths stored more C in forests than shorter ones. This was also true in a larch-dominated boreal forest in China (Jiang and others 2002), western Canadian boreal forests (Seely and others 2002), forests in the United Kingdom (Dewar and Cannell 1992; Thornley and Cannell 2000), and tropical plantations (Schroeder 1992). At a very general level, this result is due to two facts related to inputs versus removals of C. First, the average input through photosynthesis generally increases as rotation interval increases. Although in our model gross primary production decreased when forests reached their maximum height at around 200-300 years, this did not alter this basic trend in average NPP over the interval between disturbances. Thus the longer the rotation interval, the higher the average NPP input to the system. Second, the proportion of C removed also controls the steady-state or in our case the average store of C (Olson 1963). In the case of harvest of live C, the longer the interval between harvests the lower the effective proportion of C removed per harvest. This removal effect would also be true for site preparation treatments such as prescribed fires that remove C from dead stores.

Although the majority of studies have examined complete harvest of trees, several have examined partial harvests. When clearcuts are employed, whole tree harvest reduces forest C stores more than removal of just the stem (Jiang and others 2002). Thinning within stands between complete harvests generally decreases C stores in live and total forest C stores (Dewar and Cannell 1992; Balboa-Murias and others 2006). Partial harvest within a stand leads to intermediate levels of C stores in forests (Thornley and Cannell 2000) between the unharvested system and the complete harvest system. Both results make sense relative to the balance of inputs versus outputs described above. Thinning with complete harvest reduces the input and also increases the proportion of C removed during a rotation interval. Partial harvests at the stand level also reduce average inputs through NPP and also increase the proportion of C removed relative to the no harvest system, but to a far less degree than the complete harvest system.

Despite the preponderance of evidence that short intervals between clearcut harvests of stands store less C in forests than long ones, there are those promoting the use of short rotation plantation systems to sequester additional atmospheric C. To some degree this originates from the failure to correctly scale time-specific stand results to the long-term, broader scale (Harmon 2001). Although it may be true that particular ages of young forest remove more C from the atmosphere than older (or younger) ages, one needs to consider the C balance of all age classes present in a disturbance regime. Forests lose C immediately after disturbance; the amount is dependent on the amount of legacy C remaining in the form of dead material and in soil as well as the rate at which the new forest reestablishes (Harmon in press). This initial period of C loss often offsets the later period of C uptake. Because one cannot have older forests without younger forests, it is quite possible for the later periods of gains to be completely countered by the earlier period of C loss. Indeed, that is why in all systems analyzed to date, C stores in forests oscillate about a mean over the rotation unless one is transitioning from one disturbance regime to another (Dewar and Cannell 1992; Smithwick and others 2007). If a shorter rotation is replaced by a longer one, the amount of C stored in the system increases. If a longer rotation is replaced by a shorter one, then the amount of C stored in the system decreases. Thus, replacement of a long natural disturbance cycle by short rotation forestry generally leads to decreases in C stores in the forest system (Harmon and others 1990). Conversely,

replacement of a short natural disturbance cycle by a longer harvest cycle generally leads to increases in C stores (Kurz and others 1998; Seely and others 2002).

Another possible explanation for suggesting short rotation harvests is that this will increase C stores related to forest products. Our results and those of others (Dewar and Cannell 1992; Liski and others 2001; Pussinen and others 2002; Seely and others 2002) show that the average amount of C harvested per year decreases once a peak is reached at relatively short rotations that are near the culmination of mean annual increment. If forest products could be created without C loss in manufacturing and use, then harvesting forests at the culmination of mean annual increment would maximize C stores in forest systems provided enough time elapses. Unfortunately, with the possible exception of biofuels which directly count as fossil fuel offsets, almost all forest products suffer significant losses in manufacture and use (Harmon and others 1996). Those studies that have included forest products in the analysis, including ours, have found that forest products do not comprise a large fraction of the forest systems C stores (Dewar and Cannell 1992; Pussinen and others 2002; Seely and others 2002; Harmon and Marks 2002). The fraction of total forest system C stores comprised by forest products increases as rotation interval decreases, but these are relative gains and not gains in the entire system; they just offset a fraction of the losses occurring in the forest.

Our assumption that a constant fraction of harvest, regardless of rotation length, is converted to long-term stores might be challenged, as shorter intervals between harvests may lead to a smaller fraction being converted to long-term forest products (Bourque and others 2007). This would mean, for example, that the total system C stores for the 100% cut for short rotation intervals would be closer to the low storage system results; conversely for the longer rotation intervals the values would be closer to the high storage system results. On the other hand, more small trees are being converted to long-term products with improved milling technology, which might tend to make the conversion rates to long-term products similar to that of larger trees. For partial harvests, short intervals between partial stand harvests may produce trees that can be converted into long-term forest products. Rather than model all these complexities, we chose to simulate two extreme cases which can be used to model any set of assumptions regarding the effect of tree size on the storage of forest products. Moreover, although a more realistic model might modify

the exact shape of the curves, it would be unlikely to change the basic conclusion that forest products are not the major share of total system C stores.

Although we estimated the stores in forest products, we did not include the so-called substitution effects of using wood versus other more energy intensive materials for construction. As pointed out by Hennigar and others (2008), there is little consensus on the values to be used (that is, they vary 10-fold). The other issue is that these estimates represent maximal values that assume that all future buildings will be primarily constructed of materials other than wood. Thus, it counts the substitution effect over an over even when a wooden building is replaced by a wooden building. Although this assumption simplifies calculations, it does not necessarily lead to reliable estimates of the most likely substitution effect over time. If we counted the substitution effect based on the sustainable store of wooden buildings and assumed half the harvest was devoted to building construction, then the additional "store" due to substitution would have been in the range of IO_{ta} 100% of the average forest products store we reported depending on the substitution effect assumed (0.2-2 Mg C for each Mg C of building stores). Although this would have made the total systems' curves in Figure 9 flatter, with the shorter rotations more similar to the longer ones, it would not have made the partial harvests store less C than the 100% harvest. This is because the forest stores for all harvest systems are highest for the shorter rotation intervals.

There are conditions in which forest management can increase C stores relative to existing systems. Intermediate rotation intervals can increase C stores over longer rotations when there is a major decline in live C stores in older forests (Johnsen and others 2001). It is clear that altering species can greatly change the mean C store over a rotation and replacing a slowly growing species with one with rapid growth can decrease the time to reach a given C store (Dewar and Cannell 1992; Liski and others 2001; Hennigar and others 2008). Similarly, increasing nutrient availability through fertilization or improved soil management can also decrease the time to reach a given C store (Pussinen and others 2002; Jiang and others 2002; Seely and others 2002). Although we are unaware of any examination of the effect of changing decomposition rates on forest C stores, reducing decomposition rates would likely increase C stores, thereby slowing decomposition rates may also reduce rates of nutrient cycling and ultimately reduce inputs through NPP.

Our simulation experiments ignored the effect of changing climate. Climate change is likely to have multiple effects on rates of nutrient cycling, decomposition, and disturbance. The exact effect is likely to be very much dependent on the site in question. Simulating a warmer climate in Finland, Pussinen and others (2002) found that forest C stores decreased largely because increased losses in soil C were not offset by increases related to NPP. A warmer and potentially drier climate may also lead to the increased disturbance by fire, drought, and insects. Breshears and Allen (2002) have raised the possibility that increasing ecosystem C stores now may result in major releases in the future when disturbance increases. An analysis by Kurz and others (2008) indicated that changes in disturbance regimes associated with climate change are likely to shift Canada's managed forest from a C sink to a source in the next decades. We agree that had we factored increasing rates of disturbance into our analysis, our stores estimates would have been lower. The degree of decrease would be a function of how synchronous these disturbances are on a broad scale. If these disturbances do occur synchronously on a broad scale, then the reduction in C stores in forests could be substantial.

CONCLUSIONS

Our simulation modeling study indicates there are multiple ways to achieve similar C stores in the forest system. Our studies and those of others have shown that increasing the interval between disturbances, in our case harvests, increases the C stores in the forest ecosystem (that is, live, dead, stable, or soil). Harvesting at short intervals will result in more stores in forest products; however, because of the potentially high C losses during manufacturing, this increase in forest products stores does not completely offset the losses from the forest ecosystem. C stored in the entire forest system (that is, ecosystem and forest products) is lower when the interval between harvests is decreased. Frequent partial harvest of forest stands can store as much C in the entire forest system as long intervals between complete harvests of trees in a stand. This occurs because with partial harvest in a stand, the live C store is not reduced to zero and thus remains higher for a longer period in the rotation than when complete harvest occurs. With complete harvest of the trees in a stand, the live C store has to accumulate from zero stores. Partial harvest of trees may also lead to reduced C stores under certain conditions. This would include a change in the species present as well as the amount

of damage caused to the remaining trees. We did not examine the latter effect, but this likely could be reduced if precautions were taken during harvest, although this would increase harvesting costs. In our simulations, there was a major change in species present under partial versus complete harvest within a stand. The increased presence of western hemlock under partial harvest of stands in our simulations should have led to increased losses from live trees as the amount of heart-rot in that species is considerably higher than for Douglas-fir. However, we found relatively small differences in C stores when the species mixture of forests changed. Nonetheless, our findings on partial harvest of stands could vary in other systems depending on the degree the species change and the difference in species characteristics controlling C stores. The generality of our findings should therefore be tested in other mixed-species forest stands.

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