# AN ASSESSMENT OF CARBON POOLS, STORAGE, AND WOOD PRODUCTS MARKET SUBSTITUTION USING LIFE-CYCLE ANALYSIS RESULTS

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ABSTRACT

The study utilized the results from a life-cycle assessment (LCA) of housing construction to analyze forest products' role in energy displacement and carbon cycling. It analyzed the behavior of three carbon pools associated with forest products: the forest, forest products, and fossil fuel displaced by forest products in end-use markets. The LCA provided data that allowed us to create an accounting system that tracked carbon from sequestration to substitution in forest product end-use markets. The accounts are time-dependent since the size of the carbon pools is influenced by harvest timing; hence the size of each pool is estimated under alternative harvesting scenarios and presented over time. The analysis of the alternative harvesting scenarios resulted in shorter harvest cycles and provided the largest carbon pools when all three pools were considered together. The study concluded that forest products led to a significant reduction in atmospheric carbon by displacing more fossil fuel-intensive products in housing construction. The result has important policy implications since any incentive to manage forest lands to produce a greater amount of forest products would likely increase the share of lands positively contributing to a reduction of carbon dioxide in the atmosphere.

*Keywords:* Wood products, market substitution, carbon pools, avoided emissions.

## INTRODUCTION

The most recent IPCC report (IPCC 2001) concluded that global change is occurring. The report also recommended that a life-cycle analysis is needed to describe the fate of stored carbon in industrial applications. Energy embodied in wood products has been recognized to be an important carbon pool (Koch 1991). Yet there have been few analyses that tracked the movement of carbon from forest to forest product end uses and accounted for embodied energy and their carbon emission implications.

Wood products can displace fossil fuel emissions by substituting for non-wood products that utilize more fossil fuels in their manufacture. A life-cycle assessment of wood-using sectors provided the data that were used to evaluate the energy displaced by alternative materials and their consequence on carbon cycling. Few studies, to our knowledge, have investigated this question using a LCA of wood-using end markets. Glover et al. (2002) presented a life-cycle assessment of wood versus concrete and steel in house construction and concluded that houses built primarily of wood required lesser amounts of energy in their manufacture, construction, and use, but did not link the carbon pools of forest and forest products markets. Borjesson and Gustavsson (2000) took a different approach and examined greenhouse gas balances in building construction and demolition. They examined the contributions of building materials and their uses after use and demolition, explaining that when biogas is collected from landfills and used to replace fossil fuels, the net greenhouse gas emission would be insignificant.

The present study analyzed the movement of carbon and energy displacement from forests to forest products markets. It created a carbon account for three carbon pools of forests, forest products, and fossil fuel substitution to determine the pool sizes. It differs from the recent life-cycle assessment by Glover et al. (2002) and Borjesson and Gustavsson (2000) in that the carbon account considers all three pools: the forest stock, the product stock, and the product market implications of carbon emissions from fossil fuel use. The forest stock carbon pool is represented by standing vegetation and increases usually by delaying or eliminating harvests. When harvesting is considered, the product carbon pool is considered as carbon transferred from standing vegetation to some product with a specified lifetime. The third carbon pool is more complex and is associated with energy displacement and avoided emissions. We also considered using biomass as a fuel for energy rather than using forest products in end uses that compete with alternative materials and displace energy embodied in their manufacture. We considered all three pools and focused our efforts on understanding the third pool since it has received less attention, and since the recent completion of the LCA for house construction provides the data that allowed us to estimate the size of the carbon pool associated with wood product substitution.

## STUDY APPROACH

The study approached the problem of evaluating the sizes of forest and forest product carbon pools by creating an accounting method that tracked carbon from forest to product end use. We followed the approach suggested by Sampson and Sedjo (1997). The method accounted for forest carbon, carbon in products, and fossil fuel substitution carbon. The sum of these three components was defined as total carbon and was measured on a per hectare basis. We also considered time since timing of harvests throughout the lifetime of a forest, including the decision not to harvest at all, influences the development of the carbon pools. Comparison of total carbon across alternative harvest timing decisions and the no harvest scenario were made to assess how these pools changed over time and what impact forest products had on carbon emissions.

The study utilized several models that tracked carbon stocks and emissions from reforestation to forest product use. Models at the forest level were combined with models that described product use and their associated emissions at the product end-use level. We briefly discuss the models and their use in the sections that follow, and refer the reader to Perez-Garcia et al. (2004) for further elaboration of these models.

## MODELING DESCRIPTION

Forests are sources of commercial timber and wood fiber products, and these activities need to be accounted for in carbon budgeting. Without doing so, forest harvesting is usually considered to cause a net release of carbon from the terrestrial biosphere to the atmosphere (Houghton et al. 1983; Harmon et al. 1990). Expanding the boundary beyond the forest edge leads to carbon stored in the product pool, and a third carbon pool associated with energy displacement and avoided emissions. The pool of products enters the marketplace and competes with other products that also have embodied energy used in their manufacture. The substitution of fossil fuel-based energy and products by wood biomass can further decrease the emissions of carbon to the atmosphere (Schlamadinger and Marland 1996; Kohlmaier et al. 1998).

The carbon account was created using a suite of models that can be customized to different site conditions. We used conditions for the west Cascades area of the Pacific Northwest region. Tree list inventory data combined with growth and yield model simulations and the Landscape Management System (LMS) (Oliver 1992) were used to simulate inventory conditions through time and create the forest biomass account. Multipliers based on the literature review then took various biomass components and converted them into carbon on a per unit basis. The forest module calculated the various forest biomass carbon pools accounting for changes in growth, mortality and decomposition. Products were exported from the forest module to the product module, which then calculated carbon pools in products, as well as the carbon associated with energy use in their manufacture and house assembly.

Use of the forest biomass module required that a tree list be entered into the LMS, which tracked tree and stand development through time including diameter information. The diameter was used to estimate various biomass components using Gholtz (1982). Biomass was converted into carbon using Birdsey (1992, 1996). Forest components included the canopy, the stem, roots, litter, and snags. The module also considered their decay. Canopy biomass was composed of foliage and branches and was 5% to 10% of the total biomass. Stems, composed of the tree trunk and bark, were assumed to make up 65% to 70% of the total biomass. Coarse roots were assumed at 20% to 25% of total biomass and carbon in litter was assumed to be 10% of foliage and branches (Spies et al. 1988; Edmonds 1979; Grier and Logan 1977). Assumptions about the volume in snags were based on mortality predicted by a growth model, adjusted for the density of snag class, and were less than 0.5% of total biomass (Canary et al. 2000).

Carbon decomposition is modeled following Aber and Melillo (1991).

$$X_t = X_0(1 - k^* t) \quad (1)$$

where $X_t$ is the biomass at time t, $X_0$ is the initial biomass, k is a species-specific constant describing the biomass loss per year, and t is time in years. k = 0.16 for litter, 0.5 for snags and coarse roots (Turner et al. 1995; Harmon and Sexton 1996; Canary et al. 2000). More complex, nonlinear decay models could easily be incorporated but are not likely to alter any conclusions.

The products module was based on LCA data produced by the Consortium for Research on Renewable Industrial Materials (CORRIM) (Bowyer et al. 2004). The module tracked carbon pools associated with production of forest products from the forest through to end use in the housing sector. Products that were exported from the forest as commercial volume were first converted into biomass and then into carbon using species-dependent density factors (Birdsey 1992, 1996). We used the results of sawmill studies (Bowyer et al. 2004) to distribute the commercial volume into long- and short-term products. Roughly 50% of the forest carbon in a harvest was exported to lumber, a long-term product. The remaining 50% of carbon was exported to wood chips, sawdust, bark, and shavings—all short-term products or hog fuel used for the production of energy. Short-term products were assumed to decay at 10% per year (Harmon et al. 1996; Winjum et al. 1998). Hog fuel was decomposed in the production of energy. Long-term products were assumed to decompose at the end of the useful life of a house, which was set at 80 years, within the range estimated by CORRIM (Bowyer et al. 2004). Harvested timber volumes per acre were converted into product volumes, then to mass expressed in kilograms per cubic meters. Mass is then converted to carbon units considering moisture content.

Carbon flows associated with alternative building techniques with competing materials were analyzed using energy consumption and air emissions related with the manufacture of products utilized in the housing sector. Meil et al. (2004) provides an analysis of home construction in two markets with these competing materials. The study utilized a life-cycle analysis to quantify the carbon emissions and converted them to a per hectare basis to be compatible with the forest carbon account.

We utilized scenario analysis to quantify the effects of alternative harvesting cycles on the carbon accounts and a no-harvest alternative that produces no wood products. The no-harvest scenario is not equivalent to existing natural stands since it included initial stocking and no disturbances. However, using the no-harvest scenario offered some insight for an afforestation-without-harvest scenario.

Finally we created a carbon account for each harvesting scenario and for each pool. The pools are the carbon in forest stocks, product stocks, and the emissions associated with their manufacture and use in construction, a displacement pool. We also considered biomass as potential energy in our analysis for co-products that could be used as biofuel. The forest stock included canopy, tree stems, snags, litter, live roots, dead roots, and when harvesting occurs, emissions of carbon. The product stock included product carbon (both short- and long-lived). It included the transporting and manufacturing emissions associated with the production of the long-lived products that are used in housing construction. The transporting and manufacturing emissions associated with non-biofuel co-products were not tracked so as to be consistent with the assumption that their use would carry their own burden. We illustrated the option of using most low-valued co-products as biofuel, thereby transferring their burdens to the long-lived products. The embodied energy account included emissions associated with the use of substitute long-lived products in the housing market.

## RESULTS

The results describe the carbon in the three pools. The first pool consisted of carbon in forest stocks. A presentation of how carbon was exported from the forests to products follows. The third pool considered product substitution and the emissions associated with the use of substitute products in the housing market. The element of time was included in each pool. The results indicated that shorter rotations contributed to fewer carbon emissions since the impact of reducing the use of fossil fuel-intensive, non-wood products more than offsets the effect of the reduced carbon stored in the forest.

Extending the harvest cycle increased the store of carbon associated with the forest pool. This result is consistent with previous results found in Franklin et al. 1997; Burschel et al. 1993; Houghton et al. 1983; Harmon et al. 1990; Cooper 1983; Dewar 1990; and Schlamadinger and Marland 1996. We illustrate the result in Fig. 1, where the forest carbon stocks over time under four alternative scenarios are presented. Carbon in metric tons per hectare increased as the forest grows, declined sharply as harvests take place, and responded with renewed growth under all scenarios except with the no-harvest scenario. Under the no-harvest scenario, carbon increased for several hundred years assuming no major disturbance. Keep in mind that the assumption of initial stocking followed by no disturbances is not representative of old forests under natural conditions, so it should be interpreted with caution. The no-harvest scenario demonstrated a hypothetical upper bound to forest growth as might an afforestation scenario. Empirical yields for existing old forests in the Northwest contained only slightly more carbon than the 120-year rotation as a consequence of uneven stocking and disturbances, whereas this hypothetical upper bound suggested much more carbon.

The area under each curve is the cumulative carbon in the forest and included carbon pools for the stem, crown, root, litter, and dead or dying biomass. One can observe that over time, the most carbon was accumulated under the no action scenario, followed by the scenario that allowed a clear-cut harvest to occur every 120 years, then the 80-year harvest scenario, and finally the 45-year harvest scenario.

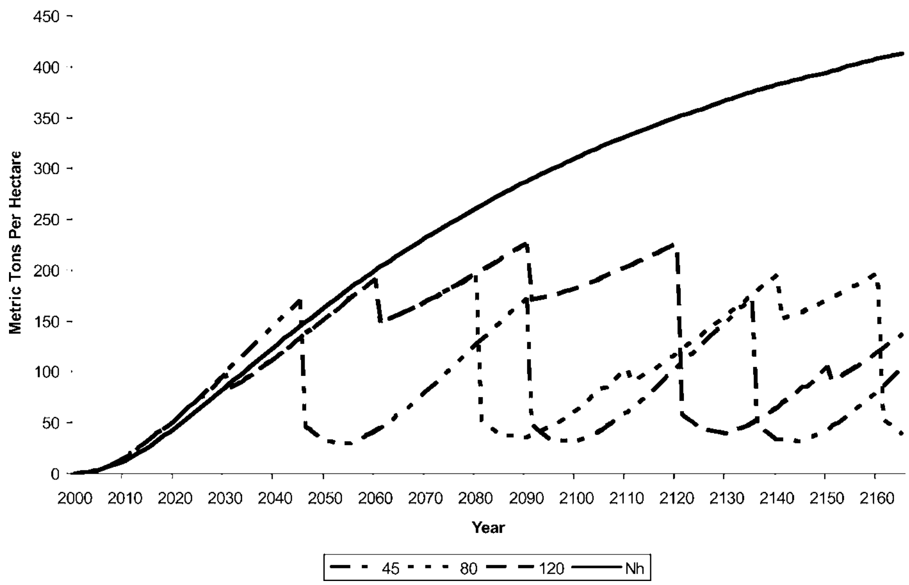


FIG. 1. Carbon in forest pools for different rotations.

Extending the harvesting cycle by longer rotations increased the store of carbon in forest and product pools as the decomposition of coproducts is effectively delayed. The fate of harvested carbon needs to be accounted for, however. As forest carbon is exported into products, product carbon pools develop. These product pools more than offset harvesting and manufacture emissions. There was no carbon associated with products under the no-action scenario since this scenario did not export products. For the longer harvest cycle scenarios, the product pools developed much later in time than for the shorter ones. The carbon in short-lived products was assumed to decompose completely during the rotation period contributing no long-term increase to the products carbon pool over time.

Alternatively, any portion of these short-lived products can be used for energy production, which would reduce purchased energy needs of sawmilling. The effect of such a decision was that the energy produced, and the carbon emissions saved, by substituting for fossil fuels becomes a permanent carbon pool instead of a short-lived product that is rapidly decomposing. A longer-term pool than even wood products in buildings, which eventually decompose, was created under such an energy substitution scenario. But in the very short term, there was a loss in the short-lived products pools as the efficiency of the conversion of wood to energy was lower than gas-fired boilers (or coal). The net impact was a small displacement of fossil fuel-derived carbon in the short term, but accumulating with each harvest. The decomposition of the long-term products was assumed to take place at the end of an 80-year useful life of the house which could more correctly be modeled as a distribution with some houses removed earlier and others later with no material change on long-term comparisons.

The substitution effects took place as wood entered the marketplace and competed with alternative materials in end uses such as housing. Without wood products, fewer wood houses would be built and more concrete- or steel-framed houses would be constructed. The energy burden that each product carried has implications for carbon emissions. Figure 2 summarizes the carbon pools for the 80-year harvest cycle including the carbon resulting from displacing cement-framed houses as wood products are produced. The increasing trend in carbon pools is substantially greater with the substitu-

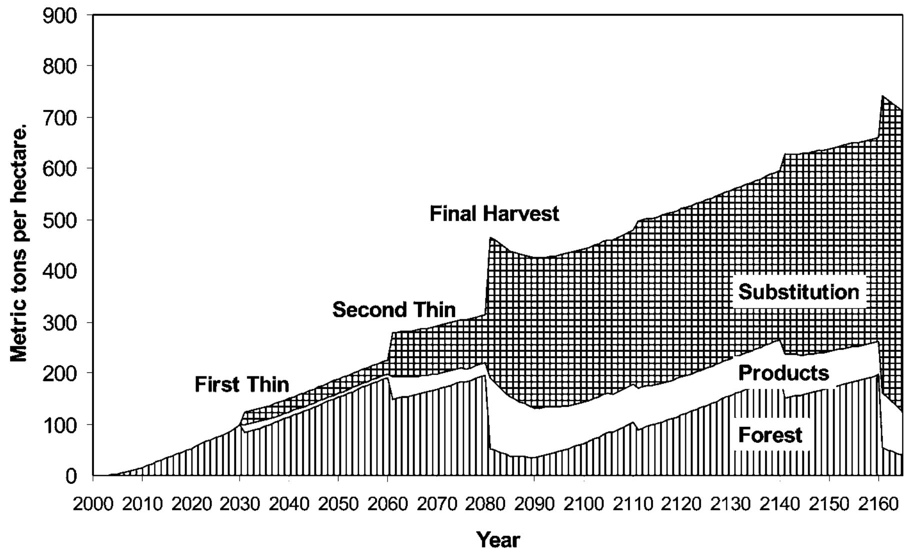


FIG. 2. Carbon in the forest and product pools with concrete substitution for the 80-year rotation.

tion of wood for cement, the second most prevalent framing material in the residential housing market.

Table 1 summarizes the carbon account averages for the time intervals of 0–45, 0–80, 0–120 and 0–165 years for each of the harvest scenarios and product pools (forest, products net of processing emissions and displaced fuel use,

TABLE 1. *Average annual carbon at specified intervals.*

| | Averages (tonnes per hectare) | | | |
|---|---|---|---|---|
| | 0–45 | 0–80 | 0–120 | 0–165 |
| | 45–year rotation | | | |
| Net forest | 70.60 | 67.30 | 71.25 | 74.45 |
| Net products | 0.00 | 24.74 | 45.38 | 50.72 |
| Net forest, products | 70.59 | 92.03 | 116.63 | 126.96 |
| Net forest, prod, displacement | 70.59 | 95.56 | 125.46 | 142.20 |
| Net for, prod, displace, substitution | 70.59 | 165.69 | 266.18 | 360.28 |
| | 80–year rotation | | | |
| Net forest | 60.46 | 106.90 | 94.45 | 110.50 |
| Net products | 3.63 | 11.22 | 36.92 | 46.96 |
| Net forest, products | 64.10 | 118.12 | 131.37 | 157.46 |
| Net forest, prod, displacement | 64.24 | 119.58 | 138.27 | 169.75 |
| Net for, prod, displace, substitution | 72.63 | 150.76 | 253.16 | 348.81 |
| | 120–year rotation | | | |
| Net forest | 60.46 | 106.95 | 137.38 | 121.30 |
| Net products | 3.63 | 11.32 | 21.08 | 41.39 |
| Net forest, products | 64.10 | 118.27 | 158.85 | 163.66 |
| Net forest, prod, displacement | 64.24 | 119.69 | 163.14 | 174.12 |
| Net for, prod, displace, substitution | 72.63 | 150.87 | 232.20 | 330.64 |
| | No harvest scenario | | | |
| Net forest | 60.17 | 124.03 | 185.53 | 238.55 |
| Net products | 0.00 | 0.00 | 0.00 | 0.00 |
| Net forest, products | 60.17 | 124.03 | 185.53 | 238.55 |
| Net forest, prod, displacement | 60.17 | 124.03 | 185.53 | 238.55 |
| Net for, prod, displace, substitution | 60.17 | 124.03 | 185.53 | 238.55 |

and substitution). Figure 3 summarizes these impacts for each harvest and time interval. Unlike the previous charts, which showed carbon increasing with longer harvest cycles, the figure indicates an inverse relationship between harvest age and sequestered carbon with the least amount of carbon stored with the no-harvest scenario. When the fossil fuel burdens in substitute products were included, the shorter harvest cycles gained the benefit of this displacement sooner. While it is true that over the very long term, the increased volume coming from longer rotations would eventually overtake the early shortfall in products, the time frame for this crossover would appear to be in the hundreds of years and beyond any interval of interest for policy.

## DISCUSSION

The paper used an LCA and constructed an accounting scheme that considered carbon from forests to end-use markets of forest and competing products. The accounting scheme combined three carbon pools: the forest pool, the product pool, and the product substitution or energy displacement pool. This last pool included the energy-use and carbon-emission implications of competing products.

The result indicated that a shorter harvest cycle does not lead to greater carbon emissions into the atmosphere. The shorter cycles produced more wood products sooner, thereby reducing fossil fuel-intensive substitutes earlier in time. Forests managed under short rotations sequestered less carbon than forests managed over longer rotations, but avoided and displaced emissions associated with production and use of energy-intensive, competing products. Avoided emissions generally exceeded any reductions in sequestration in the forest associated with a longer harvest cycle. The net result was that more carbon was sequestered in the forest and wood products under short rotations when the embodied energy pool was included.

In this study we examined mitigation options available through forestry and forest products use in the economy. The implications of recognizing forest management's positive role in sequestering carbon is important since it could be used as an incentive to increase active management of forestlands. Increasing the productivity of these lands through greater investments in forest management could lead to significant

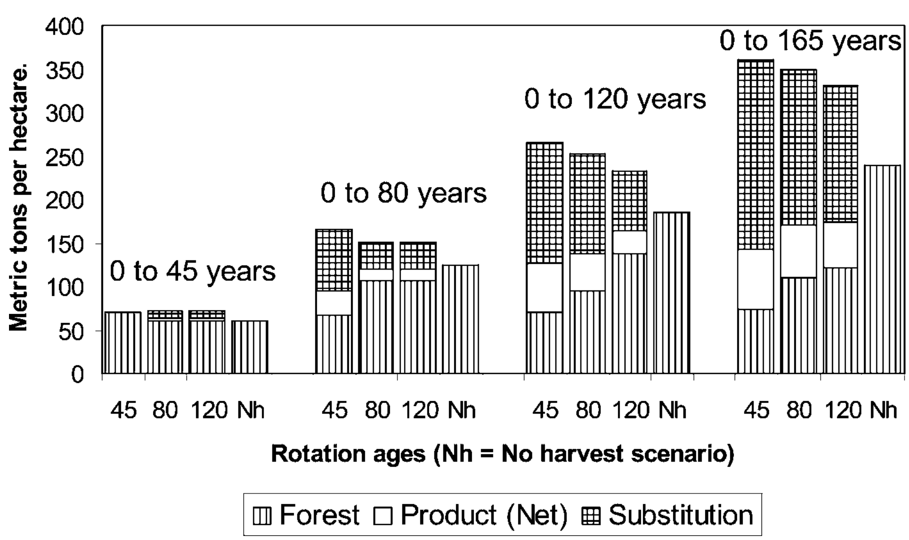


FIG. 3. Average annual carbon in forest, product, and concrete substitution pools for different rotations and specified intervals.

gains in reducing atmospheric carbon. We show that, while actions on the part of a forest landowner to intensify his or her forestry practices may lead to less carbon stored in the forests, it created a positive carbon leakage through greater use of wood products in the market place. The term leakage is used since most of the impact of intensive management on carbon pools occurs outside of the forest management project boundary. The leakage is positive since it reduced emission to the atmosphere. The effect of producing and using more wood products reduced consumption of more fossil fuel-intensive products in home construction. This research suggests that the proper boundary condition for carbon and wood flows extends beyond the perimeter of the forest area whenever wood is harvested for products.

## CONCLUSIONS

The study analyzed carbon from sequestration in a forest to substitution of fossil fuels emissions from construction materials. When carbon stocks accounted only for forest sequestration, the longer the harvest cycle, the greater the amount of carbon removed from the atmosphere. Even if we were to consider the export of carbon from the forest into product markets, and even if the rate of exported carbon was greater than the rate of tree growth, conversion inefficiencies and eventual decay limited the amount of carbon removed by forests from the atmosphere. Only when product substitution was considered in the analysis did we find that forestry can lead to a significant reduction in atmospheric carbon by displacing more fossil fuel-intensive products. Recognizing only the carbon stored in forests incorrectly subsidizes the no-harvest scenario or lengthening harvest cycles. An incentive for more intensive management would likely increase the carbon stored in the total of all three pools considered in this study.

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