Carbon sequestration in the Pacific Northwest: a model.

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

University of Washington

2002

Program Authorized to Offer Degree:
College of Forest Resource

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Acknowledgements

The author wishes to express sincere appreciation to the Silviculture laboratory at the University of Washington for their support and friendship, and especially to Professors Bruce Lippke, John Perez Garcia, Chad Oliver and Robert Gara for their patience and knowledge. Funding for the completion of this thesis was provided by the Rural Technology Initiative (US Forest Service) at the College of Forest Resources and the Columbia Pacific RC & EDD. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect the view of the funding agency.

This thesis would never have been completed without the encouragement of my family and friends.

1. INTRODUCTION

Carbon dioxide is the highest emitted greenhouse gas in the world today, mostly due to fossil fuel based energy industries and deforestation (Fung 1994). The Kyoto Protocol (UNFCC 1998), the first attempt to reach global consensus on how and how much to reduce greenhouse gas emissions, described in length two key prospective solutions to the problem of balancing the carbon cycle: reduce emissions and/or sequester more carbon. The challenge is to go back to this perceived notion of equilibrium, when the quantity (mass) of greenhouse gases entering the atmosphere balances with the quantity of greenhouse gases leaving the atmosphere.

Forest and forest products have an essential role to play in the carbon cycle mitigation process because they respond directly or indirectly to the two Kyoto premises. Reducing greenhouse gas emissions can be achieved by controlling and avoiding land use changes. Deforestation in the tropics alone amounts for about 20 % of total greenhouse emissions (Chomitz 2000). Using wood products that replace more energy intensive products with the same function is also part of the solution (Koch 1991). Bettering forestry related technology and management, therefore reducing energy demands for growing, harvesting and processing wood should also be considered.

On the sequestration aspect, the role of forests is essential in counteracting the carbon dioxide build up. By converting carbon dioxide to oxygen and carbohydrates through the process of photosynthesis, forest ecosystems have the ability to “sequester” carbon from the atmosphere. Carbon sink enhancement can be achieved by the afforestation of croplands and pastures, by increasing agro-forestry activities and by reforesting harvested areas (Birdsay et al 2000).

Sequestration can be defined as the net removal of carbon dioxide from the atmosphere into long lived carbon pools. These carbon pools are composed of live and dead above and below ground biomass, and wood products with long and short life and potential uses. According to the Kyoto protocol, there are three ways in which the carbon sequestered in these pools should be accounted for: afforestation, reforestation, and additionality. Afforestation implies growing trees where there were none before; reforestation addresses the idea of re-growing trees where some have been harvested, and additionality deals with the positive difference in sequestration achieved through management when compared to a base case scenario.

Generally, any approach should seek to balance emissions from forest ecosystems and the management of such, with environmental stewardship and economic growth as objectives. This is not a simple task, since it includes broad emissions inventories, emissions projections, data collection, oversight, and associated protocols. Carbon tax and carbon credit systems have been proposed to motivate increased carbon storage and/or reduce emissions (Marland et al 2001). Any system will require a credible accounting protocol to avoid counterproductive efforts. Since the Pacific Northwest is one of the most productive ecological areas of the world (Franklin & Dyrness 1973, Fujimori et al 1976, Grier & Logan 1977), and an important player in the USA forestry sector (Haynes & Weigand 1997), the creation of a carbon accounting model for the Pacific Northwest region is needed.

The carbon sequestration model is a step forward in developing a complete and interconnected set of accounting practices allowing for an accurate and credible analysis of past, present, and future carbon emissions relating to forestry in the region. The model is a tool meant to be of help in the assessment and resolution of trade offs at different levels in the management of forests in the Pacific Northwest region. It is very important to remember that although most of the sequestration and emission of carbon happens at the molecular scale, management decisions to enhance sequestration will be conducted at the stand and landscape levels. To cut or not to cut: this crucial question can only be addressed when the carbon issue is analyzed on a broader spectrum. The model incorporates accounting from the standing forest to the product level, wood-steel substitution dynamics in construction and biofuel displacement of fossil fuels, together with emissions from the forest operations and manufacturing activities.

Issues such as increasing the stock of carbon in the existing forests (additionality), together with more efficient harvest techniques and greater usage of wood in long lasting products (such as steel substitution in construction), and the displacement of fossil fuels by biofuels should be considered when addressing the carbon question and its possible trade offs in time and space.

Can forests be managed to meet the multiple goals of providing habitat, wood products, economic returns and carbon sequestration? The carbon model is one more tool available to managers to help in the attempt and realization of this goal.

2. LITERATURE REVIEW

It has been widely acknowledged that global anthropogenic emissions of carbon dioxide and other greenhouse gases may seriously affect the global climate system. The disruption of this cycle can have significant consequences on life as we know it (Hansen, 1988; Schneider, 1989; IPCC 1992). In 1996, 150 countries signed the United Nations Framework Convention on Climate Change (Anonymous 1992), with the objective of achieving the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Much effort is currently focused on ways of reducing carbon dioxide contributions to the atmosphere going from researching the science to understanding the fundamental biological and ecological processes in unmanaged and managed terrestrial ecosystems, to the development of protocols and new policies to address this global environmental dilemma. Carbon dioxide is one of the greenhouse gases that cause the earth's atmosphere to warm up, allowing the short-wave length solar radiation to come in, but trapping much of the long wave out going radiation. This interaction is a major determinant of global temperatures and many scientists believe that the average global temperature has risen by .5 to $1^{o}C$ in the last century (IPCC 1992). Today's atmosphere contains about 370 parts per million CO_2, as compared to about 280 ppm before the industrial revolution, and levels are increasing at about 0.5 % per year (Brady 1996).

Carbon is the foundation of life. All living tissues have carbon atoms in their composition and the cycle of this element is basically the cycle of life in our planet. The carbon cycle involves the soil and all vegetation and animal life on earth. Plants absorb carbon dioxide from the atmosphere and through photosynthesis, capture the carbon molecules for energy and build up of structural components. Part of this carbon returns to the atmosphere soon after being processed through respiration. Other parts stay as standing biomass for some time, returning to the cycle as organisms die and decompose. Some of the standing biomass will eventually be eaten by animals, with half of it exhaled immediately, the other returned as bodily wastes to the soil later in time. Once in the soil, microorganisms metabolized them, gradually returning them to the atmosphere, or leaching out as carbonates through the soil (Figure 1).

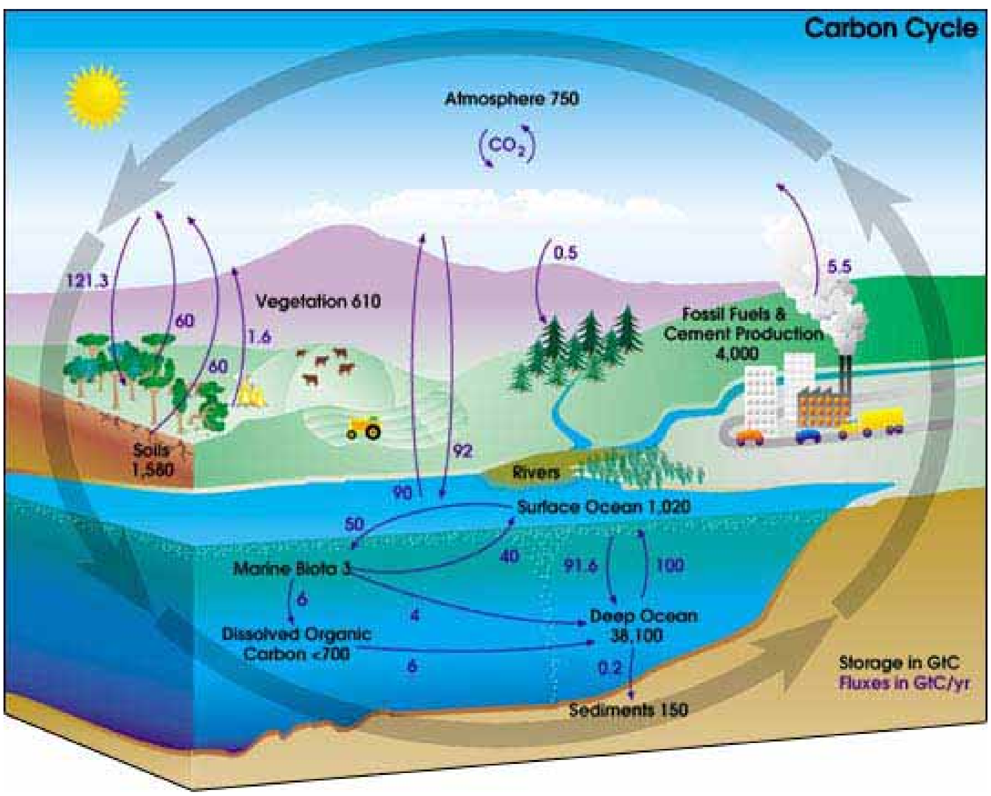

Figure 1. The carbon cycle on Earth. Illustration from NASA Earth Science Enterprise

Understanding the factors and processes driving and influencing the cycle of carbon in a particular ecosystem is critical to achieve proper management of the aboveground biomass and soil organic matter, whether it is for reducing greenhouse gas emissions or improving soil quality.

2.1. Forest Ecosystems

Forest ecosystems have essentially three carbon pools: the living biomass, detritus (debris from dead plants and animals) and soils. Soils contain almost twice as much carbon as the aboveground vegetation and the atmosphere carbon combined (Brady 1996). Through the decomposition and the accumulation of organic matter, soils have a major effect on the regulation of the carbon cycle. When soil and aboveground organic matter decline, atmospheric carbon increases, with global consequences, such as the greenhouse effect. Potential mechanisms for reducing net carbon emissions through increased carbon sequestration include the forest ecosystem together with the forest socio-economic system, with both of those systems dynamic's affecting the carbon cycle. Conservation and adaptive management of existing forests, the establishment of new forests (forest ecosystem level) and the substitution of fossil fuel based energy and products by wood biomass (forest socio-economic system) could further increase the fixation of carbon from the atmosphere (Kohlmaier et al 1998).

Forests store carbon as they accumulate biomass, but forests are also commercial sources of timber and wood fiber. In most carbon accounting budgets, 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). As the debate about controlling or mitigating atmospheric carbon dioxide concentrations moves from the study of the scientific issues to a search for practical solutions, a central question becomes whether commercial use of forests could be managed to contribute to terrestrial sequestration of carbon. Can forest management practices be developed so that they meet the multiple goals of providing wood and paper products, economic returns from natural resources, and also sequester carbon from the atmosphere?

In managed forests, the amount of additional carbon sequestered will be determined by three factors: the increase of standing carbon biomass due to land use changes and increased productivity, the amount of carbon remaining below ground at end of rotation, and the amount of carbon sequestered in products and energy, including their disposal (Johnsen et. al. 2001).

As stated previously, forests represent a huge storage of carbon since they hold about 80 % of the carbon fixed in the living biota, and much interest and effort has been put into their study, because of the possibility of being directly altered by human activity (Apps & Price 1996). The role of forests, as sink and sources of carbon in the carbon cycle, is not static at any spatial or temporal scale. Temporal changes in the forest ecosystem carbon pools are mainly driven by the dynamics of the carbon pools. Keeping track of the ecosystem processes, including population dynamics, is a crucial part of the carbon assessment. This assessment should be done at the stand level, which is believed to be the appropriate scale for such analysis (Apps & Price 1996; Harmon 2001). Forest ecosystems are complex, dynamic and diverse. Forest stands can be complex, dynamic and diverse. They all have however, three carbon pools: the living biomass, detritus and soil pools. All of these components have a role in the carbon cycle dynamics. The soil, a natural body of organic and inorganic materials and living forms, provide the substrate for plant growth. Detritus, the debris from dead plants and animals, is a source of storage as well as a source of food. The live biomass, which includes above and below ground pools, composed of coarse and fine roots, understory and canopy, captures carbon dioxide while releasing oxygen, and also respires, releasing part of the carbon dioxide previously absorbed.

A more detailed literature review will be given first for soil, followed by above and below live biomass. Lastly, the detritus component will be explored, including plant debris (litter fall) and harvest residuals (slash).

2.1.1 Soils

Conversion of natural to agricultural ecosystems has lead to drastic perturbations in the processes governing the soil organic carbon dynamics. Deforestation, biomass burning, plowing, residue removal, fertilization and single crop cycles have been depleting the earth's soils in most agroecosystems by 50 to 70% (Lal 1995). The effects of forest management on carbon soil storage are not as clear nor as well understood as in agricultural systems. Estimated carbon storage in below-ground components is known and has been measured (Brady 1996), but it is mostly how harvesting and management affects the soil carbon where knowledge is lacking.

Soil carbon has been found to be strongly dependent on the stand composition and climate (Schlesinger 1977), therefore very hard to model. Organic carbon in the root zone accounts for approximately 2/3 of the carbon in terrestrial ecosystems worldwide (Post et al. 1982). It is less responsive to harvest than the litter fraction because of its long residence time. Turn over rates encompass a large range. Post et al (1982) estimated a turn over rate of 0.00083 per year, although faster turn over rates have also been shown: 0.013 per year (Gardner & Mankin 1981) and 0.025 per year (Schlesinger 1977).

Harvesting can have a significant increase or decrease effect on forest floor biomass, mostly based on how much slash is left behind after the operation (Johnson 1992). The majority of studies however, showed little or no change in the soil mineral carbon after harvest, with less than 10 % increase or decrease (Fernandez et al., 1989; Johnson et al., 1991; Aztet et al, 1989, Huntington and Ryan, 1990; Alba and Perla, 1990; Lawson and Taylor, 1990; Raich 1983). Exceptions are usually found after harvesting in tropical areas, where soils are poor and the environmental condition are proper for rapid decomposition. Houghton et al (1983) developed a global carbon model, in which the assumption is that after forest harvest, tropical, temperate and boreal ecosystems loose 35, 50 and 15 % of litter and soil carbon. Harmon et al (1990) assume no change in soil carbon although noted that most probably soil organic matter would decrease with intensive forest management.

Fire, be it a prescribed or a wild fire, will reduce the carbon and the overall floor biomass, the effects depending primarily on the intensity of the burning, with the upper 15 cm., the surface soil, most readily influenced by land use and soil management. In the Pacific Northwest, a study found significant losses of floor biomass and nitrogen (40%) after a wildfire (Grier 1975). Another study, this time on broadcast burning, found a decrease in soil carbon (20-30%), with an equal or higher increase in the soil carbon almost two years after the prescription (40-70%) (Macadam 1987).

Carbon soil can be increased with fertilization, because of its effect on primary productivity. Effects of nitrogen fixation and fertilization on soil carbon have given results on carbon soil increasing from 30 to 100 % depending on the site and the species mix composition (*Alnus rubra* and *Ceanothus spp.*) (Binkley 1983; Binkley et. al. 1982). Despite all the unknowns and uncertainties of soil carbon dynamics and management impact on those dynamics, the commonly held assumption of soil carbon losses of 30-40% (Musselman and Fox 1991) after harvesting was not corroborated by the literature review.

2.1.2. Above ground living biomass

Different studies present a dichotomy on aboveground biomass dynamics, with some suggesting aboveground components can be a net sink (Delcourt & Harris 1980, Oliver et. al. 1990) or a net source (Houghton et. al. 1983; Harmon et. al. 1990) of carbon. Both cases are correct. The analysis and assertions on what an ecosystem's carbon is or will become under a certain line of management will depend on what was the state of the ecosystem before any management was conceived. Furthermore, it will depend on how extensive is the spectrum under which carbon cycling is considered. For example, Harmon et al (1990) argued that the conversion of old-growth forests to younger forests under current harvesting and use conditions has added and will continue to add carbon to the atmosphere, even when considering long term products such as lumber. Oliver et al (1990) found similar results at the forest ecosystem level, but further argued the conversion of old growth to managed stands is negligible when compared to the addition of carbon by the burning of fossil fuels. Similar results were found by Schlamadinger and Marland (1996). This is why it is very important to establish first and foremost the spectrum under which the carbon accounting story will be evaluated. Nobody would deny that an old growth stand stores more carbon at the forest level than a younger stand, and that the younger stand has a greater primary productivity, with higher rates of yearly uptakes of carbon. With these differences taken into consideration, the above ground living biomass is further analyzed.

In the development of a forest, the foliage, litter fall, net primary production and nutrient accumulation in above ground tree components usually reach a plateau at the stem exclusion stage (Tadaki 1966, Gessel & Turner 1976, Oliver 1981, Sprugel 1985). This trend seems to be true for Douglas-fir as well (Turner & Long 1975) and directly impacts the development of biomass through time in the different components.

The distribution of standing forest biomass in representative stands in the Pacific Northwest region has been previously estimated (Grier & Logan 1977, Keyes 1979, Edmonds 1980, Vogt et al 1980, Gholtz 1982, Cooper 1983, Keyes & Grier 1981, Santantonio & Herman 1985, Vogt et al 1986, Edmonds 1987). The total biomass and forest carbon will depend on the stand conditions, its age, density, species composition, etc. However, the patterns of biomass distribution in conifer stands of the forests of the Pacific Northwest are very similar and roughly as follows: 65-75% in the stem and bark, 15-20 % in coarse roots, 5-10 % in the crown (branches and foliage). Biomass in stem and bark on a 40 year old Douglas fir stand on a high productivity site was about 76 % (Cooper 1983), and this proportion was about 73 % in a low productivity site planted with Douglas-fir (Keyes & Grier 1981). Similar values have been established for old growth Douglas-fir in western Oregon (Grier and Logan 1977).

Looking at the components on conifer stands separately, a nearly complete foliage cover is established early in stand development of most forests and remains essentially constant until maturity (Grier & Logan 1977, Keyes 1979, Cooper 1983). Branches, as extensions of the stem, can accumulate carbon through the life of the tree. The fraction of biomass in branches is usually higher for hardwood stands, with as much as 25 % of the biomass found in that component. This proportion is much smaller for conifer trees, with about 5-7 %. The stem biomass increases rapidly with age while the foliage biomass stays fairly constant (Grier and Logan 1977).

Carbon content is approximately 50 % of the oven dry weight (Reichle et al 1973, Harmon et al 1990) with slight differences related to the chemical and physical composition of some of the components (Vogt 1991).

2.1.3. Below ground living biomass

The importance of roots as structural, storage and physiological organs has been acknowledged for quite some time (Harris 1971, Santantonio 1977). However, they have not been, for the most part, included in ecosystem research because of the difficulties surrounding their study. Observations are not possible without major disturbances in the soil, while changing dramatically the environment of the roots.

The development and buildup of the roots biomass is more complex than some of the above ground components. This is due to the variety of roles played by coarse and fine roots: structural support, food storage and nutrient absorption for example. However, in their 1992 study on spatial disposition and extension of the structural coarse root system of Douglas-fir, Kuiper & Coutts found significant positive correlations between all the coarse root parameters studied and the tree diameter at breast height (dbh). Furthermore, data on the relationship between coarse root biomass and dbh in Douglas-fir in the Netherlands was found to be consistent with natural stands of Douglas-fir in the Pacific Northwest (Santantonio et al. 1977), even though the site conditions and management history between the two sites were very different. Dbh, which is readily available, has therefore been shown to provide good estimates for woody root biomass.

Decomposition rates for woody roots in forest ecosystems of the Pacific Northwest were estimated by Chen et al. (2001), with Douglas-fir roots having an estimated decomposition rate of 0.05/year for roots between 4 and 12 cm.

Fine roots on the other hand are very hard to account and simulate based on growth models. An extensive study on fine root biomass related to stand age and productivity found no significant differences among stands of different age but same site productivity (Vogt et al 1987). Another study did a sensitivity analysis dealing with the incorporation of fine roots biomass into the soil carbon, leading to the assumption of fine roots flux being relatively constant (Cropper and Ewel 1984). In biomass studies and budget estimations, fine roots biomass estimates from previous studies are added to the total estimated by the simulations (Harmon et al 1990, Keyes & Grier 1981), or total root biomass is based on a percentage of the bole (Bruschel 1993), but none of the studies from the literature reviewed provided a potential way of simulating their growth and death.

2.1.4 Forest floor

2.1.4.1. Plant debris

Carbon accumulation in detritus and soil often accounted for greater quantities of biomass than the living biomass, especially on hardwood stands (Schlesinger 1977, Covington 1981, Gholz & Fisher 1982, Moore & Braswell 1994). The return of organic litter to the forest floor is complex and very variable. Factors to consider among others are: the age of the stand, the species composition, the density of stand, the site productivity and the environmental conditions (Bray & Gorham 1964). It is clear that litter-fall plays a fundamental role in soil formation and site productivity (Bray & Gorham 1964, Schlesinger 1977, Covington 1981, Gholz & Fisher 1982, Moore & Braswell 1994). It is also clear that both the carbon chemistry and nutrient concentrations of litter strongly affect its decomposition (Aber et. al. 1990). Thus, detrital mass changes more rapidly than soil carbon with disturbances.

The amount of change when harvest occurs will be highly dependent upon the harvesting method, the stand composition and the climatic conditions (Cooper 1983). Harvesting usually increases decomposition rates of the detritus material because it causes higher soil temperatures and moisture, together with increased availability of inorganic nutrients needed by decomposers (Aber et al 1978). Temperature and moisture variables have been found to be the main factors explaining decomposition patterns, stronger when considering them together rather than individually (Gholtz et al 2000). Turner and Long (1975) showed that leaf litter (which has the highest concentrations of nutrients and decomposes faster) decreases in time, but total tree litter increases in time because of returns of less decomposable woody litter. Similar results were found in old growth Douglas-fir ecosystems, where woody material represented about 60% of the biomass returns (Grier et al 1974). A study on Douglas-fir stands ranging from ages 22 to 160 showed that a typical leaf litter production is 2 MT/ ha/ year, while total litter is in the ranges of 2.5 MT/ ha/ yr (Gessel & Turner 1976). Annual fall of litter increases until about age 40, and then becomes relatively constant while total litter continues to increase because of woody litter, although it can be very irregular.

Dimock (1958) showed what intuitively seems correct with regards to thinning operations: decreasing levels of litter fall with increasing intensity of thinning regimes on Douglas-fir stands.

The decomposition of coarse woody debris although little understood, is a very important aspect of nutrient cycling in forest ecosystems of the Pacific Northwest (Harmon 1992). Turner and Long (1975) calculated decomposition rates for an age sequence of Douglas-fir stands. The decomposition rate starts at about 0.05 /year for a young stand, and increases to about 0.16 /year at age 30, decreasing to about .1 /year at age 50 and above.

2.1.4.2. Logging debris: slash

Slash burns are very rarely done anymore and have not been done for most of the last 20 years because of smoke. On the west side of Washington Cascades, on slide ground, the slash is left unburned unless whole tree yarding is the harvest method. In the case of whole tree yarding, logs are processed by a delimber and slash is burned on the landing. On gentler terrain, where the cut-to-length system is used for thinning, slash remains unburned. When shovel logging is the harvest technique for a clearcut, burn piles are created and combustion is fairly complete (Mason, personal interview, 11.2001).

Harvesting can have a significant increase or decrease effect on forest floor biomass, mostly based on how much slash is left behind after the operation (Johnson 1992).

2.2 Managing for carbon sequestration: the Silviculture

2.2.1 Longer rotations

Long rotations develop structurally complex managed forests and increase the accumulated timber volume per unit area (Franklin et al 1997, Burschel et al 1993). Longer rotations are ecologically viable because Douglas-fir (*Pseudotsuga heterophylla*) and other associated conifers can live to a very old age and their productivity is maintained to advanced ages (Curtis 1997). Longer rotations should be combined with thinning regimes to increase the productivity and the size of trees in a shorter time span. Larger trees imply higher wood quality, and the thinning regimes can provide revenue as intermediate operations. Longer rotations allow for adjusting unbalanced age distributions, increasing the quality of wildlife habitat associated with late successional forests, and increasing the net standing carbon storage capacity.

2.2.2 Variable retention

The variable retention system (Franklin et al 1997) is based on the concept of retaining structural components of a particular stand for at least another rotation. The development and maintenance of a structurally complex forest is the most important point when taking about the restoration of a forest. It is very flexible and the level of retention directly relates to the management objectives. It is important to consider other functions of these structural components, beyond the carbon sequestration per se, such as the enriching attributes and enhancement of connectivity throughout the landscape. The idea is to provide structural elements for diverse habitat requirements, ameliorate the microclimatic conditions, and maintain microfauna (mycorrhizal fungi, lichens etc). Enriching stand structure by maintaining living and dead structural material of various sizes, species, and levels of decay through aggregated or dispersed retention can also be incorporated into the management of the forest. Leaving behind coarse-woody debris following thinning and harvesting operations is recommended to increase the carbon in the forest floor.

The management objectives will determine what will be retained, how much and in what pattern. Large trees with special features such as rot pockets, cavities and large limbs or clusters of limbs should be retained. Snags in different states of decay and sizes, as well as coarse woody debris in different sizes and stages of decay should also be retained. The pattern in which these structures are to be left will depend on the stand and its characteristics. Aggregated retention will be preferred at some points, and dispersed retention will be the choice on others, hopefully through the mixture achieving greater complexity and carbon sequestration. Shelterwood (Smith et al 1996) for example, is a type of dispersed retention of dominant and co dominant wind firm and stress tolerant trees, that will provide in time a well distributed source of snags and coarse woody debris.

2.2.3. Thinning regimes

Thinning can be used to promote the overall health of a forest, through reduction of high fuel loads and increased wind stability. Thinning can be used to salvage material from disturbances and avoid insect outbreaks (Smith et al 1996, Oliver & Larson 1996). This is an important consideration when addressing issues such as fire safety, insects, wind stability and diseases. More important however, thinning can be used to accelerate the stand dynamics of a particular stand, favoring certain structural components that have a functional value, releasing growing space for understory species and advanced regeneration, or simply to increase the size of trees. Thinning in restoration is used as a tool that affects the structure of the stand. Pre-commercial thinning (PCT) is applied near the end of the stand initiation to enhance survival, growth and value of the residual trees. It increases stand uniformity but promotes tree growth and understory development (shrub and herbaceous) allowing also for early establishment of shade tolerant species

(Oliver and Larson 1996). By doing a PCT, the differentiation of the stand is accelerated and the structural and species components increased. The spacing can vary in patches through the plantation, with small openings or gaps created to retain components of the early initial stage.

Thinning combined with extended rotations can maintain forest cover for long periods while still providing wood products, through allowable intermediate operations; timber flow can be sustained during intermediate stages of development with the benefit of ecological processes being maintained and higher wood quality achieved (Oliver 1993, Burschel et al 1993).

2.3 Accounting for the sequestered carbon

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (1998) prescribes that net flows into or out of the biosphere will be represented by the changes in carbon stocks. This notion simplifies the measurements and accounting processes. The Intergovernmental Panel on Climate Change (2000) is consistent with this prescription, defining carbon sequestration as an increase in carbon stocks anywhere but in the atmosphere. The important issue is "additionality" (Chomitz 2000). Additionality addresses the idea that carbon sequestration or reduced emissions can result from a management change. Management alternatives can be compared against a base line, to measure the change from "business as usual". Afforestation of grazing land for example, is a one time huge addition of carbon pools and if reforested after disturbance, the carbon pools can be maintained through a long period of time.

How do we measure carbon and how can we estimate the variations in the different terrestrial pools? Biomass is one of the key characteristics of forest ecosystems because it contributes in the definition of carbon flux and nutrients, as well as the potential standing and dead organic matter in a particular site. Biomass studies are essential for understanding ecosystem dynamics. Biomass studies are static however, describing and estimating living and dead material in a particular stand at a particular time (Santantonio et al 1977). Combining biomass studies with growth models seems to be the most straightforward manner for estimating component masses at different points in time at the stand scale. The carbon storage pattern simulated by the model is static, meaning productivity of site is assumed constant as embedded in the original inventory in question, without possible changes associated to different temporal scales, like the global warming issue. The Kyoto Protocol specifies integration of greenhouse emissions with corresponding offsets credits if carbon is removed from the atmosphere on a 5-year commitment period. Integration over spatial scale might be used as well to decrease the costs in accounting, monitoring and verification.

2.4 Forest products, biofuel and substitution

Harvesting of forest ecosystems changes the natural carbon cycle between the terrestrial pools and the atmosphere. Therefore, the balance between forests and forest products is an important component in any budget analysis and should be included.

The carbon fluxes related to the harvesting activities should follow the general equation for atmospheric flow (Winjum et al 1998): net carbon flux to the atmosphere = carbon fluxes to the atmosphere from harvesting activities and forest products – carbon sequestration during development of the forest. The carbon fluxes associated with forest harvesting activities and the use of wood should include the carbon emissions from decomposition of slash left in the forest after harvest, the burning of fuelwood, the waste from manufacturing wood products, and the decay of the products pool.

Over a long term period, the amount of carbon stored in the biosphere reaches a steady state, and continuing mitigation of carbon emissions depends on the degree fossil fuel use is displaced by biofuel and wood products (Schlamadinger & Marland 1996).

Fossil fuel substitution or conservation through wood usage is based on the idea that a prevented or avoided emission is avoided forever and wood is renewable. Wood can be regrown, and if sustainably managed, a biomass supply can be continuous and dependable (Bergman & Zorbe 2001). Beyond the renewability issue, environmental advantages of using wood biomass for energy include the lack of net carbon emissions from the burning of the wood because it equals the carbon absorbed during the lifetime of the tree and the fact that wood does not contain sulfur or heavy metals that cause acid rain pollution. There is also the economic advantage. On general terms, wood fuel is less expensive than fossil fuels if the wood used for energy comes from low value wood, such as material from thinning operations or undesired understory growth.

A modeling study comparing the growing of trees to sequester carbon vs. growing trees to substitute fossil fuels showed that many factors influence this trade off. Important variables were: forest productivity, the efficiency of the production of wood based energy, previous land uses and the time scale considered (Marland & Marland 1992). The benefits in terms of using wood as energy instead of leaving it in terrestrial pools of storage increased with increased productivity of the site, with greater time intervals considered and with the efficiency and usage given to the biomass products.

There is also the idea that forest products require less energy in their manufacture than other products for the same use. If wood products can replace more energy intensive products with the same function, the substitution by wood products will also provide a decrease in the carbon emissions to the atmosphere (Koch 1991). Aluminum, steel, cement, bricks and synthetic materials derived from fossil fuels cause a greater energy consumption and greater carbon additions to the atmosphere. For example, the net energy required per ton of lumber studs is 2.91 million BTU (oil equivalent). The net energy required per ton of steel studs is 26.67 million BTU (Koch 2001).

The Intergovernmental Panel on Climate Change (1990) recommendations and guidance with regards to response strategies in the forest management context included the replacement of fossil energy sources by sustainably managed sources of biomass, increase substitution efforts of highly energy consuming products by wood, technology improvement with regards to the use of fuel wood, and encouragement of the recycling of forest products to provide even longer storage for carbon pools.

2.5 Carbon credits

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (1998) has proposed a way for establishing limits on greenhouse gas emissions to be enforced internationally, with different types of commitments for developed and developing countries. The protocol allows, within a set of rules, for countries to use their terrestrial sinks to offset part of their greenhouse gas emissions from other sources.

The idea of emission trading has also been included in the Kyoto protocol. Countries listed in Annex B of the protocol can offset their own emission reduction commitments by engaging in emission reduction activities in another Annex B country (developed) or a non Annex B country (developing). The protocol is however unclear if carbon sequestration can be used the same way the emission reductions activities are carried between Annex and non Annex B countries. Among other issues to be resolved before the Kyoto protocol can be implemented internationally and commitments enforced internationally, is that accounting rules for emissions and reductions need to be tested and put in place (Marland et al 2001).

The potential use of carbon sinks in forests and other terrestrial pools to offset emissions from other sources has been criticized on several grounds (Shlamadinger and Marland 2000). Increasing carbon sinks differ from reducing emissions in three ways: the permanence issue, the saturation issue and the verifiability issue. Shlamadinger and

Marland argue that carbon sequestration if found successful is still not permanent. Furthermore, if again there is success in accumulating carbon sinks in terrestrial systems, there is a limited time for these sinks to grow until they reach saturation levels. A last point they make is that if these operations are successful, they must be accountable and verifiable. At present time there is no agreement on a standard accounting system for terrestrial pools. However, it is recognized that even without the permanence issue resolved and with limits in the sink capacity, there is value in delaying emissions regardless of the long term considerations of the sequestered carbon. Marland et al (2001) argues that when reductions are clearly permanent (fossil fuel substitution and reduction) credits can be sold. On the other hand, when emission reductions are not clearly permanent, emission credits could be rented instead. They further argue that although some individual projects might be temporary, the aggregate economic incentives for carbon sequestration will increase the carbon sequestered on a permanent basis. Where incentives exist (either tax credits or direct payment) for carbon sequestration, more sequestration should occur. Chomitz (2000) also recognizes the value of temporary carbon sequestration and among many other reasons he makes the following points: it postpones climate change and it buys time for technological progress to develop alternative ways to avoid greenhouse gas emissions.

Birdsey and Heath (1997) estimated on a large scale assessment that over the past 40 years, US forests have sequestered enough carbon to offset approximately 25 % of the current US emissions. Creating a market for reducing carbon dioxide emissions through forest sequestration requires three elements: a market framework, demand from willing buyers and supply from willing sellers. For a market framework to be successful, it requires a policy and political framework. Willing buyers come from consumers interested in reducing their emissions. They need insight about the options that forest conservation and management provide in terms of reductions and mitigation. The third part has to be about providing the supply: landowners understanding the carbon dynamics of their forest, how to increase it through management and how to access the markets.

One last point: trying to protect the global climate through carbon sequestration, by coming up with efficient accounting mechanisms that encourage carbon sequestration in forests and forest soils also provide incentives for other desired activities such as the sustainable management of natural resources and protection of biodiversity.

3. METHODS

A prototype carbon sequestration analysis model was developed for the West Cascades of the Pacific Northwest region. It is to be used with tree list inventory data and growth and yield model simulations of inventory conditions. Microsoft Excel © was selected for use as the spreadsheet program with which to build the carbon storage model.

The model was designed to be easily adapted and updated. Certain carbon factors can be very specific to a particular area and new knowledge is constantly being acquired on the carbon cycle and its components and should be considered if pertinent. Due to the complexity of the carbon cycle and to the accuracy of the carbon model created, carbon storage evaluations are done at the stand level (Apps & Price 1996; Harmon 2001). The complexity of carbon accounting, and the success estimating a carbon balance for the system, increases with the increase of the spatial and temporal scales: the more complex the hierarchy of the system, from individual tree to the landscape level, the more complex its representation and estimation.

The carbon model is an attempt to develop a closed carbon model in which all flows into and out of the system are mathematically accounted for. It is at the input and output level where simplifications were made so that forest carbon balance questions could be defined. It is assumed the forest occupies an area of uniform site quality. Also, that changing climatic conditions and CO_2 concentrations do not affect processes and their rates, and that repeated harvesting does not reduce long term site productivity.

There are two main parts in the carbon model: the forest module and the product module. The displacement and substitution analysis are derived from the products module.

A critical aspect of the model is that it has to be functional and applicable to a wide array of forest management scenarios and stand conditions. For the forest module part of the model, which is the base of the carbon model, the data required is taken from the Landscape Management System (LMS©) (McCarter et al 1998). LMS is an evolving software application developed at the University of Washington- College Of Forest Resources- Silviculture Laboratory. LMS is designed to assist in landscape level analysis and planning of forest management alternatives. It is implemented as a Microsoft Windows (TM) application that coordinates the activities of other programs (projection models, visualization tools, etc.) that makeup the overall system. Since LMS is modularly designed, it can accept many growth model alternatives for use with simulations.

LMS was utilized to perform projections of inventory conditions providing a broad spatial and temporal context for carbon storage evaluation at the tree and stand levels over a variety of growth and treatment periods. For the PNW forest simulations, the PNW variant of the Forest Vegetation Simulator (FVS©) (Wykoff et al 1982) was selected as the growth model for use within LMS. FVS is a distance independent growth and yield model based on individual tree records. These tree records (diameter, height crown ratio, TPA, etc.) will define growth for small and large trees, as well as mortality, which is density dependent. FVS allows modification of the response of the growth model, making it possible to adjust for specific stand conditions. The PNW variant applies to 37 species from the region. It can portray single or mixed species, even and uneven aged, on a wide variety of forest types. The simulations and analysis are concentrated on conifers and specifically within the *Pseudotsuga menziesii* and *Tsuga heterophylla* (Franklin and Dyrness, 1973) forest types.

3.1 The Forest carbon

The carbon forest module includes the following components: branches (dead and live), foliage, stem and bark, standing dead trees (snags), coarse roots and litter (harvest slash, dead branches and foliage). Forests are considered a standing pool of carbon at any point in time.

The forest module of the carbon model is based on accounting for all allocations through biomass estimates at discrete points in time, which establishes where and how much is sequestered in what components. This allocation changes in time through losses by decomposition, and harvest operations that use fossil fuels.

Carbon additions or reductions to atmospheric pools resulted from forest growth, silvicultural treatments and decomposition. These additions (sequestration) and reductions (emissions) were calculated as the difference between total estimated forest carbon storage the growth period before treatment and total estimated forest carbon storage for the growth period post treatment (Figure 2).

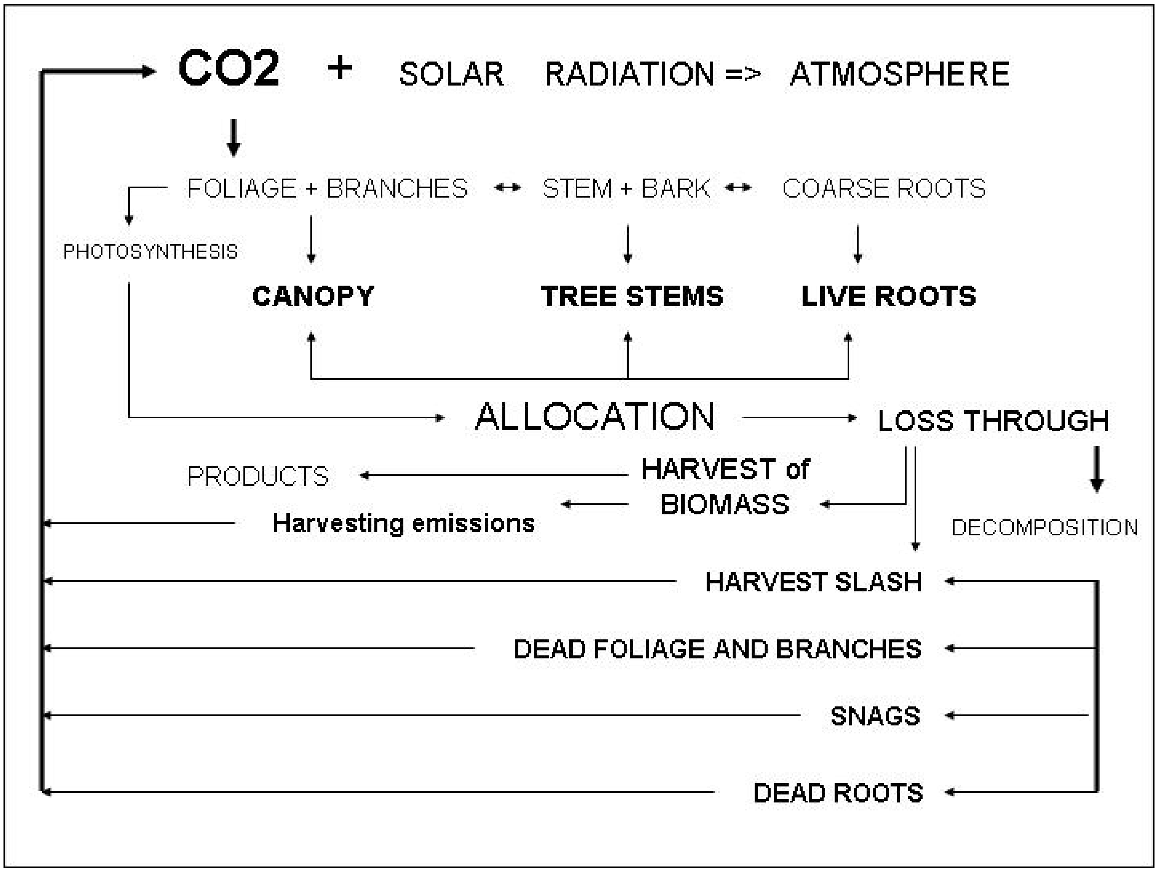

Figure 2. Forest module based on carbon sequestration (additions) and carbon emissions (reductions).

Soil carbon changes were ignored due to the complexity of assessing carbon budgets through time after silvicultural operations, and from the leaching of organic and inorganic carbon at that level (Harmon et. al. 1990). Research attention has been given to below ground processes, respiration and foliage dynamics (Landsberg et. al. 1991), and as information becomes pertinent should be integrated to the system.

The model has been developed for 5 year growth periods, but LMS allows for an increase of this time for operations assessed with 10-year growth periods, in which case equations would account for this change.

The first step is to convert the LMS scenario tables for the forest, the cut and the snag inventory from English to metric units to be consistent with the units required for the regression equations used. The scenario table shows individual tree records with its respective attributes for all the management periods considered. Regression equations developed by Ghotlz et al (1979) were used to estimate tree component dry weight biomass based on diameter at breast height (d.b.h.) for branches, foliage, stem, bark, snags and coarse roots in kg/ ha. High correlations are usually found in logarithmic regressions of dry weight on d.b.h. According to Bunce (1968), this is in part due to the balance between apical and radial growth, and because logarithmic units represent progressive orders of magnitude. The estimation of current and total foliage biomass using d.b.h. has been shown to have errors in the regression, especially in older stands, and this should be taken into account (Grier & Waring 1974, Snell & Brown 1978, Marshall & Waring 1986). All results however, are benchmarked against biomass estimates found in the literature (Grier & Logan 1977, Keyes 1979, Edmonds 1980, Vogt et. al. 1980, Gholtz 1982, Cooper 1983, Keyes & Grier 1981, Santantonio & Herman 1985, Vogt et. al. 1986, Edmonds 1987, Vogt 1991). The equations, unless cited otherwise, follow the form:

(1) $\ln Y = a + b \ln X$,

where a and b are regression coefficients, Y is the dependent variable and X is the independent one. The equations are species and component specific and have been used in several biomass studies in the region to determine dry matter production (Grier and Logan 1977, Gholz 1982, Cropper and Ewel 1984, Vogt et al 1987, Harmon et al 1990, Canary et al 1996). Derived from equation (1), the equations for biomass (B) follow one of the three forms, depending upon species and component (Appendix A):

(2) $B = e^{b0} * dbh^{b1}$

(3) $B = b_0 + b_1 * dbh^2 * ht/100 - b_2 * (dbh^2 * ht/100)^2$

(4) $B = b_0 + b_1 * (dbh^2 * ht/100)$

where b_0, b_1 and b_2 are regression coefficients that are species and component specific (Ghotlz et al. 1979). Standing carbon was estimated by multiplying the biomass output by a proportion factor that depends on the species and component, but averages 50 % of dry weight (Reichle et al 1973, Harmon et al 1990, Birdsay 1992). The carbon output is then summarized into three groups: stem (bark and trunk), crown (foliage and branches) and soil (coarse roots). The understory carbon pool represents approximately 1% of forest carbon (Turner at al 1995). Since this is a small percentage of the total forest carbon pool and because models are not available to link understory biomass to tree inventories, estimations of understory carbon storage were not included in this project.

The woody debris pool consists of snags, dead coarse roots and litter fall. The largest pool of organic carbon in most forest stands is soil organic matter and detritus (Schlesinger 1977). Litter mass changes more rapidly than soil organic matter. For the purpose of this project no loss of soil carbon was assumed due to harvest as indicated by three major studies (R. Boone et al 1988, Harmon et al. 1990, Johnson 1992). It is also assumed that the carbon flux of fine roots is balanced: fine roots grow and die at the same rate (Santantonio et al. 1977, Cropper & Ewel 1984). Therefore, organic soil carbon was determined to be relatively constant and was not included in the overall equation for carbon pools.

Litter fall was defined as a variable percentage of the total foliage and branches biomass, with an average of 10% of the foliage and dead branches total biomass assumed to accumulate in the litter pool for the 5-year growth period (Franklin and Spies 1988, Edmonds 1979, Grier and Logan 1977). The litter fall pool increases after each treatment because foliage and branches are assumed to be left scattered on site. This means that on the west side on steeper slopes the slash is left unburned unless whole tree yarding is the harvest method. On the gentler terrain where the cut-to-length system is used for thinning, slash remains unburned. Again, for simulation purposes, foliage and branches are considered to decompose on site instead of being burned.

Root biomass of harvested trees was also accounted for and decomposed through time, adding this biomass to the live root biomass pool.

Snags were determined by the tree mortality predicted by the FVS growth model. The general equation for calculating snag biomass (SB) uses species specific equations for live trees corrected for density (Canary et al 1996):

(5) SB = (biomass of live tree stem (Gholtz et. al. 1979) * density of snag (Spies 1988)) / density of live tree (Hartman et al. 1976)

The snag carbon content was estimated by multiplying the snag biomass times the species carbon factor, which is very close to the live tree carbon factor. The change in carbon content with regards to the biomass of the component remains relatively constant between live and dead trees (Sollins et al 1987). Existing stumps were not considered in the carbon pool, because data on those components was not available for calculation.

The reduction of the different biomass pools, such as snags, litter fall and coarse roots were estimated by decomposing them according to species specific annual decomposition rates developed by Harmon (1993)(Appendix A) based on the literature (Harmon et. al. 1986). They have been evaluated and used by major studies (Turner et al 1995, Birdsay 1996). Estimation of subsequent reductions of carbon from the decomposing components from the forest module were calculated using the following equation:

$$(6)\ X_t = X_0\,(1 - k * t)\ ,$$

where X_t is the carbon biomass at time t, X_0 is the initial biomass, k is the species specific constant describing the biomass loss per year and t is time in years (Aber and Melillo 1991). The mass of decomposing material is the sum of mortality in the most recent interval (5 year periods) and the residual mass of decomposing material (X_t).

Because LMS projections work on 5 year steps, the equation generally used within the model follows the form:

$$\text{Total } Xt_1 = Xt_{0\text{->}1} + ((1\text{-}k)^5 * Xt_0),$$

where Total Xt_1 is the cumulative carbon in a certain component at time t_1, $Xt_{0\text{->}1}$ is the carbon accumulated in that component in the period t_0 to t_1, k is the decomposition rate, 5 is the number of years and Xt_0 is the carbon found in that component at time t_0.

3.2 The Carbon in Products

Carbon sequestration goes beyond what can be measured in the forest as live and standing or dead and decomposing. Forest products constitute a very important pool for capturing carbon on a long-term basis, especially when emphasizing the use of wood on long term products, such as lumber for structural components in residential construction.

Products are modeled with a constant rate of products loss to the atmosphere, as most studies that have addressed products have done (Houghton et al. 1983, Harmon et al 1990, Oliver at al 1990, Dewar 1991, Harmon et al. 1996). The model does not allow for changes in time in terms of technological improvements in manufacturing efficiencies and product use, and does not include disposal since it includes continuous decomposition. The model considers the raw biomass harvested, its conversion to products through manufacturing, and the accumulation and decomposition of the product pool through time.

The products module takes all the biomass harvested at different points in time, allocating part of it to long term and part to short term carbon pools. The long term products constitute the base for the substitution assessment. The short term products are the base for the displacement of fossil fuels by biofuels. Harvesting and manufacturing emissions are also part of the carbon model accounting (Figure 3).

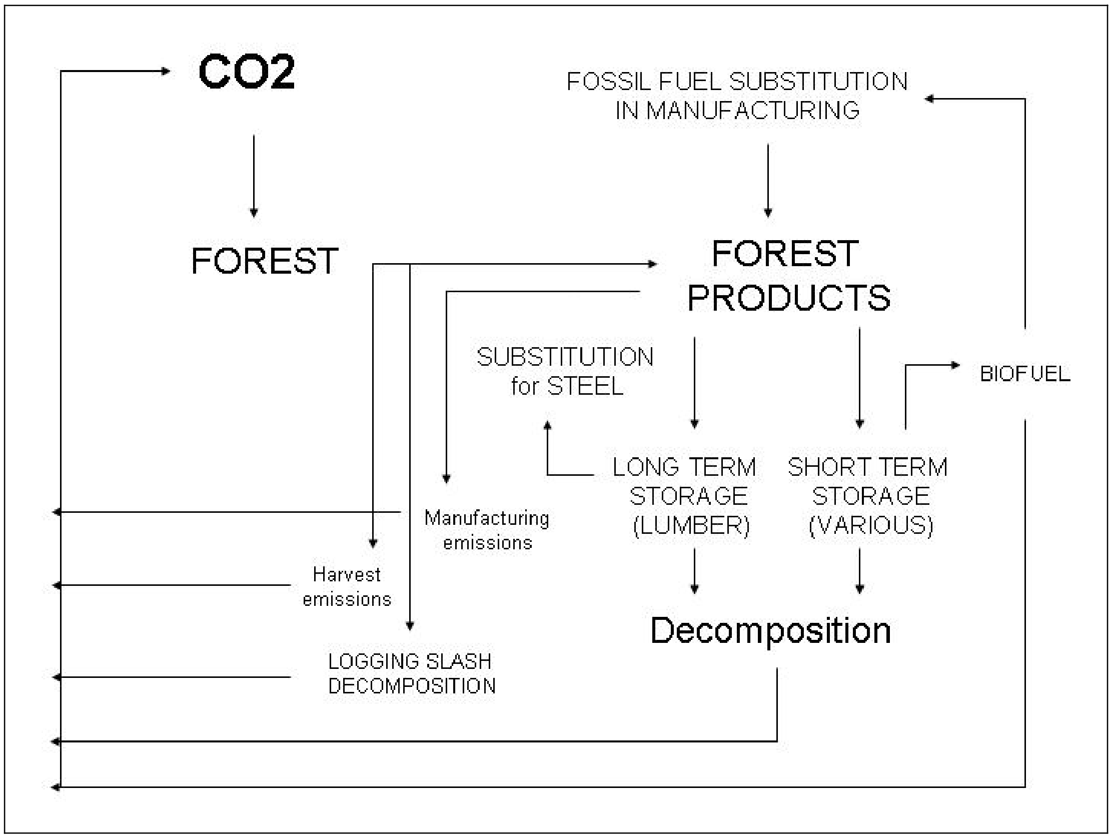

Figure 3. The products module and its components within the carbon model.

Starting with the Volume summary table from LMS, with forest and cut volumes for a particular scenario, the amount of forest products is determined by using a set of studies recently conducted in the Pacific Northwest by C.O.R.R.I.M. (2002). Four mills were surveyed in the region, producing dimension lumber as their primary output. The manufacturing process was divided in four units: sawing, drying, planing and energy generation. The numbers, coefficients and factors used in this part of the carbon model are the average values derived by weighting the production at each one of these mills (Appendix B).

The spreadsheet starts with total raw volumes of harvested material per stand given in ft^3/acre. Using an average lumber yield of 9.9 bf/ ft^3, volumes in ft^3 are converted to Mbf (thousand board feet) of dry planed lumber. In order to produce one Mbf of dry planed lumber, 101.01 ft^3 of raw logs are required. This standard yield is neither species nor diameter sensitive. The four mills reported a range from 90.4 to 105 ft^3 of logs /Mbf of lumber. A wood density of 28.08 lbs/ft^3 was used for Douglas-fir and 26.21-lbs/ ft^3 for western hemlock (US Forest Products Laboratory, 1999) to convert volumes to mass.

Table 1. Outputs in kg and lbs/ MBF of dried planed lumber in the PNW region (CORRIM 2002 App B).

INPUT wood (logs)		**OUTPUT**					
		product	**co-product**				
ft^3		wood only	bark	chips	shavings	sawdust	fuel bark
101.01	Lbs	1421.5	246.0	947.0	132.0	257.8	40.3
	Kg	644.7	111.6	429.5	59.9	116.9	18.3

Co-products from the sawing unit are added to the ones from the planning unit to give co-product totals for the manufacturing process. These totals are used as average biomass outputs for co products based on the volume units (Table 1). The outputs from this part of the products module are Mbf /volume harvested, the biomass of dry planed lumber obtained from this volume, an the biomass of co-products, in English and metric units.

The volume conversion numbers can be modified according to specific cases, for example, when greater or less efficiencies at the mills can be accounted for. These conversion numbers were taken from the average of the operations and efficiencies for the mills surveyed in the PNW region. They combine an 86% recovery at the planer, with 56 % recovery at the sawmill, giving an overall yield of approximately 48 % for planed dry lumber from raw logs. At this level of the analysis, 100 % of the harvested material was considered lumber yield material, with no differentiation towards plywood material.

The products carbon content is assumed to be approximately 50 % of the dry weight biomass (Birdsay 1996, Winjum et al 1996). Co-products are green and hog fuel is assumed to be at 50% wet base moisture content, a value given by the mills.

The carbon pools of lumber and co products were estimated to decompose according to species-specific annual decomposition rates (Harmon et al 1996, Winjum et al 1996). Estimation of carbon loss to the atmosphere through decomposition were calculated using equation (6) with specific constants describing the decomposition of long and short term storage products. The total products carbon at time 1, X_{t1}, is the sum of products harvested and manufactured in t_0 decomposed for the 5 year interval between t_0 and t_1, plus the products harvested and manufactured in t_1. This calculation works for long term and short term storage products, and the decomposition of these two products pool is calculated separately within the products module of the carbon model.

3.2.1 Carbon Emissions

3.2.1.1 Forest Operations

Carbon emissions from forest operations are based on the amount of fertilizer, lubricant and fuel consumed in the intermediate operations (pre commercial and commercial thinning, fertilization) and final operations (harvesting). Emissions from regeneration activities are not accounted for because they are not significant (Johnson personal communication. 3/2002). The amount of fuel and diesel consumption depends on the harvesting equipment, the amount of fertilizers applied at the seedling stage and as intermediate operations, the intensity of silvicultural treatments, and the distance to the mills for processing of the logs. Carbon emissions are estimated and defined based on outputs from the SimaPro model (Franklin Assoc. 1998) and Johnson's harvest factors (personal communication, 3/2002) and will be explained later in this part of the chapter.

Diesel consumed is estimated to be 0.0184 gallons/ ft^3 of timber volume extracted for the regeneration harvests, and 0.0246 gallons /ft^3 of timber volume extracted from the thinning operations (Keegan et al. 1995). The lubricant consumption is assumed to be 1.8 % of the fuel consumption (Kellog at al. 1996). Diesel for hauling corresponds to 0.0276 gallons/ ft^3 of timber volume transported (0.0006 gallons/mile of transport). Hauling production and fuel consumption include empty and loaded travels over the specified distance. This distance can be changed according to the reality of the projection. For the case studies the distance is assumed to be 35 miles one way.

By using conversion factors of 138,881 British Thermal Units (BTU)/ gal for diesel and 148,832 BTU/ gal for lubricants (Johnson 2002), the amount of BTU/ acre from the use of these two products can be determined for the amount of volume harvested on the acre and hauled from the simulated stands at any particular point in time. From this, the amount of BTU/ft^3 can be determined as well.

The harvesting and regeneration emission factors from the SimaPro model are given in kg of compound emissions/ MegaJoule (MJ) (Table 2).

Table 2. Emission factors from the SimaPro model. (Franklin Assoc. 1998).

Emission Factors from SimaPro			
	Diesel & Lub. (kg/MJ)	**Nitrogen** (kg/kg)	**Phosphate** (kg/kg)
Air emissions			
CO	3.36E-04	3.92E-05	9.63E-06
CO_2	0.00E+00	5.69E-01	3.20E-01
CO_2 fossil	7.94E-02		
CO_2 non-fossil	1.89E-05		

Joule is the metric unit for energy. The amount of diesel and lubricant in BTU/ft^3 must be converted into metric units. For this, the volume from each silvicultural operation in ft^3/ acre is multiplied by 0.7 to obtain m^3/ha. With volume and area in metrics, MJ/m^3 can be determined. The output in MJ/m^3 is multiplied by the SimaPro emission factors (kg/MJ) to obtain emission outputs in unit weight/ unit volume harvested in metric units and are converted to English units (kg/ m^3 and from that to lbs/ ft^3). Emission compounds addressed by this part of the module are: carbon monoxide (CO), fossil carbon dioxide (CO_2) and non-fossil carbon dioxide (Franklin Assoc. 1998). Fossil carbon dioxide represents the emissions from fossil fuels, and the non-fossil carbon dioxide comes from the burning of biomass in a wood boiler.

The emission numbers are presented in terms of total carbon emissions in kg/ha and lbs/acre for the volume harvested every time a treatment is performed. The amount of carbon emissions is determined by multiplying the total emissions by the atomic weight of carbon and dividing by the atomic weight of the compounds in question (CO: 12/28 and CO_2 : 12/44). Carbon emissions from forest operations are cumulative through time because less than 2 % of the emissions come from non fossil sources.

The amount of fertilizer for regeneration is estimated at 0.0009 lbs of nitrogen, 0.00016 lbs of phosphate and 0.00039 lbs of potassium/ seedling (Schlosser et al, 2001). The intermediate fertilization is assumed around age 30, with 465 kg of urea/ ha (413 lbs of urea/acre) which should leave about 225 kg/ ha (200 lbs/acre) of nitrogen in the ground. Fertilization emissions are based on an average rate of 50 ha/ hour (120 acres/hour) for the amount of fertilizer assumed (Webster, personal interview 11/2002).

Using average density of 12.97 barrels per metric ton for liquid petroleum gas (LPG), and 42 gallons per barrel, the weigh of LPG is 1.8 kg/ gallon. With an 80 % of weight in carbon, and 1.67 gallons of LPG/acre required for the running of an average size helicopter used in these types of fertilizations (Johnson 2002), the emissions are estimated to be about 6 kg /ha (5.3 lbs/acre), an almost insignificant addition, nevertheless accounted for in the process.

3.2.1.2 Manufacturing emissions

Manufacturing emissions from the production of one Mbf of planed dry lumber were exported from the CORRIM database (CORRIM 2002 unpubl.) determined by using the SimaPro model (Franklin Assoc. 1998) (Table 3). The Life Cycle Assessment protocol established that manufacturing emissions are to be accounted as burdened emissions. This means the manufacturing emissions shown in Table 3 are only 56 % of the sawing emissions and 86 % of the planning emissions, with the co-products burdened with the remain emissions.

Table 3. Air emissions from production of one MBF dry planed lumber

	TOTAL
CO	0.48
CO2 Fossil	120.00
CO2 non-fossil	22.60
CH4	0.32

Unit factors for the carbon emissions were established for the manufacturing process considering a mix of Douglas- fir and western hemlock in the production of dry planed lumber. The ratio of the mix between the two species is not considered to affect the overall air emissions, since the two species are very similar. These unit factors for CO, CO_2 fossil and non-fossil, and CH_4 are multiplied by the number of Mbf produced from the harvested volumes and summarized in terms of kg/ha and lbs/acre of carbon emissions. Drying emissions are assumed to be 0.009 kg carbon /Mbf (0.2 lb carbon/MBF) as reported by the mills and are part of the overall manufacturing emissions output. Manufacturing emissions are further summarized in metric tons/ha and thousand lbs/acre and are cumulative through time.

All manufacturing emissions in this phase of the model are considered to accumulate through time because the majority of the emissions are fossil emissions. However, this fossil fuel usage is a reflection of the mills surveyed, and not necessarily the reality of the region. In fact, more than 50 % of the energy for lumber production comes from biofuel usage according to data gathered recently. This information on the biofuel usage was just recently updated (Wilson, personal communication, 10/2002) and further adjustments within the products module need to be done to better differentiate between fossil and non fossil emissions, the emissions from non-renewable and renewable resources.

Table 4. Updated air emissions from production of one MBF dry planed lumber.

	TOTAL
CO	1.96
CO2 Fossil	95.60
CO2 non-fossil	259.50
CH4	0.25

3.2.2 Displacement of Fossil Fuels by wood

The amount of carbon stored in the biosphere reaches a steady state, and continuing mitigation of carbon emissions will depend on the extent to which fossil fuel use is displaced by biofuel (wood energy) and the level of wood products usage.

As long as the wood used for fuel in the wood boiler is replaced by new growth, there is no net increase in the amount of CO_2 released. The carbon in the fossil fuel not used, having being displaced by the usage of wood, remains in storage. This storage is cumulative through time since the displacement of fossil fuel is permanent (Burschel et al 1993). Manufacturing emissions are burdened for the use of the co-products as source of energy with 100 % of the emissions from the manufacturing of lumber together with the co-products outputs.

Numbers were taken for the energy outputs and efficiency levels for three types of boilers: wood, diesel and natural gas (CORRIM 2002). The efficiencies are 67, 80 and 80% respectively. According to the CORRIM study and the efficiency levels, 1000 lbs of hog fuel at 50 % moisture wet base, give rise to 3 million BTU (steam). When compared to natural gas, 1000 ft^3 correspond to 816,000 BTU and one gallon of diesel to 111,200

BTU (EIA 2000). After energy and volume conversions, it can be said that on an energy basis, 1000 lbs of hog fuel (50 % moisture wet base) = 26.97 gallons of diesel = 3676.5 ft^3 of natural gas, under the assumed conditions taken from the assessment of the four mills and their boilers conditions.

These factors, together with numbers taken from the Energy Information Agency (2001) on average carbon emissions from different fossil fuels are the basis for the displacement calculations. The share of co-products that are used for their fuel value varies widely depending upon their price relative to alternative energy sources. Maximum displacement at harvest uses all of the co-products (bark, chips, shavings, sawdust and fuel bark) as biomass for energy (i.e. fuel for the wood boiler). This biomass permanently displaces the fossil fuels that would have been burned to produce the same amount of energy.

With an average of 75 % carbon per unit weight, 0.0145 metric tones of carbon are released for every million BTU produced with a natural gas boiler (1000 ft3 = .816 million BTU). With an average of 80% carbon per unit weight, 0.01716 metric tons of carbon are released for every million BTU produced with a diesel boiler.

For the case studies evaluated in the applications of the carbon model, natural gas boiler was evaluated against a wood boiler; therefore the displacement equation follows the form:

Displaced carbon in Metric tons/ha = BTU produced with hog fuel/ ha * 0.0145.

3.2.3. Substitution: wood vs. steel in construction

When managing a fix number of hectares while producing more or less products through different management scenarios, substitution by other more energy intensive products will occur when wood products are not available from the fixed land base.

The substitution analysis assesses the contribution of a single hectare to the already existing mix of wood and steel framed houses for a certain region. The region, in this context the Minneapolis region, has a market in which about 100,000 new houses are build every year, with 80,000 wood framed dominant and 20,000 steel dominant. The assumption is that adding one wood house to this matrix results in the subtraction of one steel house, so that all measurements are consistent with a fixed unit of consumption, in this case a fixed number of house units providing equivalent service.

Starting from a base case scenario with a defined wood flow through time (in this case the 40 Base Rotation), the wood for about 4 wood framed houses out of the total market comes from our hectare at harvest. The contribution coming from any change in the management of our hectare to the change of that mix of wood vs. steel framed houses is what is being considered by the substitution analysis. When more wood is produced, less carbon will be emitted per hectare because less steel will be needed and less fossil fuel will be used. More carbon is emitted per hectare when wood is not available on our hectare because steel, a higher energy manufacturing product, has to be used instead of wood.

In order to do an integrated assessment of the substitution of wood for steel in construction, a whole house approach was considered (CORRIM 2002). Substitution takes place at the house level, based on two designs that differ in the materials used as structural components for the buildings: wood studs versus galvanized steel studs. Environmental impacts of the single-family house designs were assessed from harvesting to construction, limiting the scope to the bill of materials needed for the two types of designs: the wood and the steel house (App G, CORRIM 2002). The ATHENA_{tm} model was used to perform the life cycle inventory for the wood and the steel, covering life cycle stages from the extraction of the primary materials through the manufacturing and on site construction, including transportation for both house designs.

The total wood biomass required for a wood framed house is roughly double the wood biomass required in the steel framed design. The biomass harvested, in metric tons/ ha of wood at different periods in time, is the base for the assumption that wood design construction is applied when wood is harvested on the hectare and steel design construction is applied when wood is not harvested on the hectare.

There are two equations used in the calculations for substitution:

1. $X\ t_1$ (total wood harvested at time t_1) = 14.37 Hw + 7.74 Hs

   H = number of houses, w = wood, s = steel ,

   where the coefficients represent the wood mass in each house (14.37 metric tons for the wood framed house and 7.74 metric tons for the steel framed house).

2. $Hw + Hs = 1$

Solving two equations for two unknowns, the number of potential wood framed and steel framed houses is determined based on the amount of wood fiber harvested at a particular point in time:

Xt_1 (total wood harvested at time t_1) = $14.37\ Hw + 7.74\ (1-Hw)$

$Xt_1 = 6.63\ Hw + 7.74 \quad \Rightarrow \quad Hw = (Xt_1 - 7.74)/\ 6.63$

$\Rightarrow \quad Hs = (Xt_1 - 14.37 * Hw)/\ 7.74$

When no wood is harvested in our hectare, Xt = 0 and the calculation establishes that the regional matrix of houses will have 1.17 less wood framed houses and 2.17 more steel framed houses than the base case. Fractional units simply indicate the contribution share for our one hectare example.

The Global Warming Potential (GWP) index (CORRIM 2002, app G) was used for the calculation of the tradeoff in terms of carbon emissions of the construction of a wood framed house versus a steel framed house. The estimates of carbon emissions for both house designs have been calculated from the resource extraction to the construction of the buildings, with all steps in both processes accounted for. The number of houses, Hw and Hs at a particular point in time, are then multiplied by their respective GWP Index to determine the amount of CO_2 sequestered and emitted by such constructions. The GWP Index is the impact assessment in terms of CO_2 released to the atmosphere, together with the equivalent of other gases with global warming effects. The equation is as follows (EMR Canada 1990):

$$\text{GWP index (kg)} = CO_2\text{ (kg)} + [3\ CO(g) + 150\ Nox(g) + 63\ CH_4\ (g)]/1000$$

The GWP index is 39,810 equivalent CO_2 kg for the wood framed house, and 59,290 equivalent CO_2 kg for the steel framed house. These numbers are the base for the CO_2 emission substitution equation that has the following form:

$$CO_2\text{ tradeoff equivalence} = - Hw * 39{,}810 + Hs * 59{,}290.$$

This number is later converted to carbon emissions by multiplying it by the atomic weight of carbon with regards to the CO_2 molecule. If more wood is harvested at any point in time in our hectare, more wood framed houses will be built with contributions coming from our hectare, representing fewer carbon emissions per hectare.

The substitution numbers are the result of deducting the differential in carbon emissions from an alternative management scenario with respect to the 40 Base Rotation.

Because the substitution numbers come from the differential of the Base case to an alternative management scenario, if no wood is harvested in any of the hectares considered, there is no difference, they cancel each other out. The differences only arise when wood is harvested in one scenario and not in the other one.

4. RESULTS

The alternatives considered characterize the effects of changing the rotation lengths (the Rotation case) and alternative management intensities (the Intensity case). A base case scenario is selected as a reference for the analysis. The rotation analysis compares the base case to longer rotations, over different periods of time. The study evaluates carbon pools at the forest and products levels, and considers trade offs in terms of carbon displacement (fossil fuel displacement by wood burnt for energy) and substitution in construction with wood versus steel. The Intensity case assesses the effects of more intensive management, and trade offs of slightly longer rotations (10 years) combined with higher management intensities. The Intensity case, like the Rotation case, provides a detailed description of the carbon pools and its differences in the forest, in products, with displacement and substitution impacts. Finally, the economic implications for these different cases are provided.

4.1 The Rotation Case

The afforestation case is selected as a starting point because of its tutorial properties and its simplicity. Afforestation implies the establishment of a new forest on non-forested land. A typical example of afforestation is to grow trees on degraded agricultural or pasture land. Afforestation implies a one time increase in the sink capacity of a certain area, and after the first rotation has been established and harvested, the development of carbon pools is similar to a reforestation case.

The base case is selected using LMS and stand inventory data. The FVS growth trajectory was matched to the McArdle et al.(1949) yield table for similar stands. In order to create the inventory used in the rotation and management intensity case scenarios. A newly created plantation with a base site index of 128 was matched to the number of trees per acre, the quadratic mean diameter, the height and volume of a 20 year old stand from McArdle (1949). The FVS PNW variant was then adjusted to track the change in yield shown in the McArdle table, by adjusting the maximum stand density index and growth rates. With the growth model calibrated in such a way, stands with the same inventory but with different site indexes were created. An average site index of 110 was picked for the base case simulation. All of the simulations had a pre commercial thinning at age 15 and a regeneration harvest at different points in time: 40, 45 and 50 year rotations.

The three rotations were later evaluated for economic optimization. Zobrist's economic model for the Pacific Northwest region was used (2001). It provides Soil Expectation Values (SEV) for the scenarios in question. SEV is a forestry term used to describe "the present net worth of bare forestland for timber production calculated over a perpetual series of timber crops grown on that land" (Davis and Johnson 1986). Maximizing SEV is the correct way of guiding an investment, and the management decisions to achieve economic efficiency. The economic model includes management costs and a set of other variables that must be specified (Appendix D). Assuming an interest rate of 5%, the 40 year rotation produced the highest SEV at $463. The forty year rotation therefore was selected as the base case scenario for both the Rotation and Intensity case scenarios.

For the rotation analysis, carbon pools are evaluated and compared among the different rotation lengths through a 165 year management horizon. Four scenarios – the Base 40 year rotation, 80-year rotation, 120-year rotation and No Action – are examined in terms of the carbon in the forest, the products resulting from the harvest of the forest at different points in time, the potential wood biomass displacement of fossil fuels, and finally, the non-wood substitution effects due to timber volume flow and the availability of wood for construction.

The Base 40 year scenario is pre commercially thinned at age 15 to 680 trees per hectare (275 TPA). The 80 year scenario is pre commercially thinned to 680 trees per hectare, and commercially thinned twice, leaving about 2/3 of the total basal area at ages 30 and 60. The 120 year scenario is the same as the 80 year scenario prescription, with one extra commercial thin at age 90. The No Action scenario has nothing done to it and assumes no natural disturbances beyond the normal mortality. All scenarios start with 1900 trees per hectare (770 TPA), and the same number of trees is planted after every regeneration harvest (2.1* 2.4 meter spacing). Regeneration harvest under these scenarios is equivalent to zero retention at time of harvest. The No Action scenario is not equivalent to what one would expect in natural stands since they would generally have had poor stocking and contain many fewer trees per hectare.

Forest carbon results will be presented individually by scenario. Results for the carbon in products, emissions, displacement and substitution will be summarized and compared for the four scenarios combined.

4.1.1 The Forest Carbon

4.1.1.1. The 40 year scenario

The standing carbon found on site increases from zero in year 2000 to a total of 154 metric tons/ha after the first rotation. By the end of the second rotation, the standing total increases to 182 metric tons/ ha, reaches 191 by the end of the third rotation, and 196 metric tons/ha by the end of the fourth one. Total forest carbon is the amount of carbon found on live and dead components in the last year of the rotation, just prior to the regeneration harvest (Table 5). Trees used for the reforestation simulations (years 2040, 2080 and 2120) are older than the ones planted in the afforestation (2000), therefore slight differences in canopy, stem and live roots can be appreciated in the forest carbon.

Table 5. Forest carbon in metric tons/ ha prior to final harvest through time.

	2040	2080	2120	2160
Canopy	16.80	17.30	17.30	17.30
Tree Stems	105.01	110.13	110.13	110.13
Snags	1.73	2.14	2.18	2.18
Dead Roots	1.57	10.55	14.08	15.29
Live Roots	24.32	25.60	25.60	25.60
Litter	5.07	15.94	22.01	25.26
TOTAL	154.49	181.66	191.30	195.77

When compared to the total forest carbon in year 2040, there is an increase of 18 % in the total forest carbon at the end of the second rotation, a 24 % increase by the end of the third rotation, and a 27 % increase by the end of the fourth. The carbon pools are asymptotically approaching a steady state: the reforestation condition starting from the case of afforestation. The carbon in the canopy, stems, snags and live roots reaches this stability more rapidly than the carbon in the dead roots and litter.

The tree stem represents about 68 % of the total forest carbon after the first rotation, and because of the increase in the litter and dead root components through time, this percentage decreases to about 60 % in the following rotation simulations. It is the increase in the litter and dead root pools that contribute the most to the increase of carbon pools on site.

The numbers from Figure 4 for the forest carbon pools do not correspond to the numbers found in Table 4, since the figure shows the stand after having been harvested in years 40, 80, 120 and 160. This explains the increase in the litter pool and the transfer of the live root carbon pool to the dead root in those particular years. The litter and root pools will eventually reach a stable level in time, as more rotations are grown and harvested.

Soil carbon was not modeled. The way this carbon pool will be affected from the case of afforestation to reforestation, as stated in the Literature review chapter, will mostly depend on the method of harvest and the site preparation activities for the regeneration planting. However, for this evaluation it is assumed that it should have little consequence in the comparisons where the focus is on modest changes between rotation lengths.

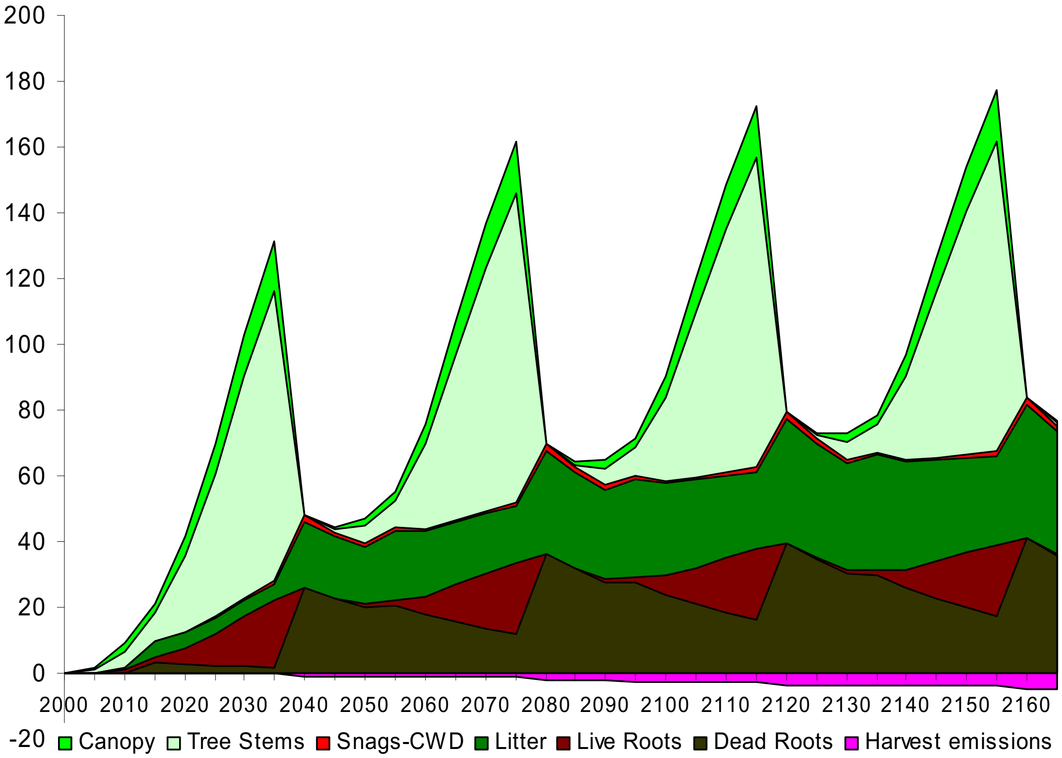

Figure 4. Forest carbon pools in metric tons/ha for the 40 year scenario (after harvests in 2040, 80, 120, 160).

4.1.1.2. The 80 year scenario

The forest carbon reaches 228 metric tons/ ha after the second rotation, an increase of 4.5 % from the first 80 year rotation (Table 6). The small percentage increase of the forest carbon pool is mainly due to the decomposition of dead roots and litter, with decomposition rates of 5 and 16 % per year respectively. The stem, canopy and live roots pools remain relatively constant, when looking at the end rotation results by the end of the second rotation.

Table 6. Forest carbon in metric tons/ ha prior to harvest through time

	2000	2080	2160
Canopy	0.00	16.16	16.37
Tree Stems	0.00	146.05	142.23
Snags	0.00	2.74	3.06
Dead Roots	0.00	7.78	14.44
Live Roots	0.00	36.37	35.12
Litter	0.00	9.10	16.71
TOTAL	0.00	218.19	227.93

The increase in the forest carbon pool is due mainly to the increase in the snag, dead root and litter component (Figure 5). The canopy carbon pool reaches about 16 metric tons/ ha at age 50 and will stay relatively constant after that age until harvesting time. The litter pool increases to 25 metric tons/ha after the first rotation, and reaches 33 metric tons/ ha after the second rotation. All the live root carbon is transferred to the dead root pool after harvest, reaching 44.15 metric tons/ ha after the first rotation and almost 50 metric tons/ ha after the second. It is expected that the litter and roots carbon pool will reach a stable asymptotic level after the stand has been carried under this management strategy for several more rotations.

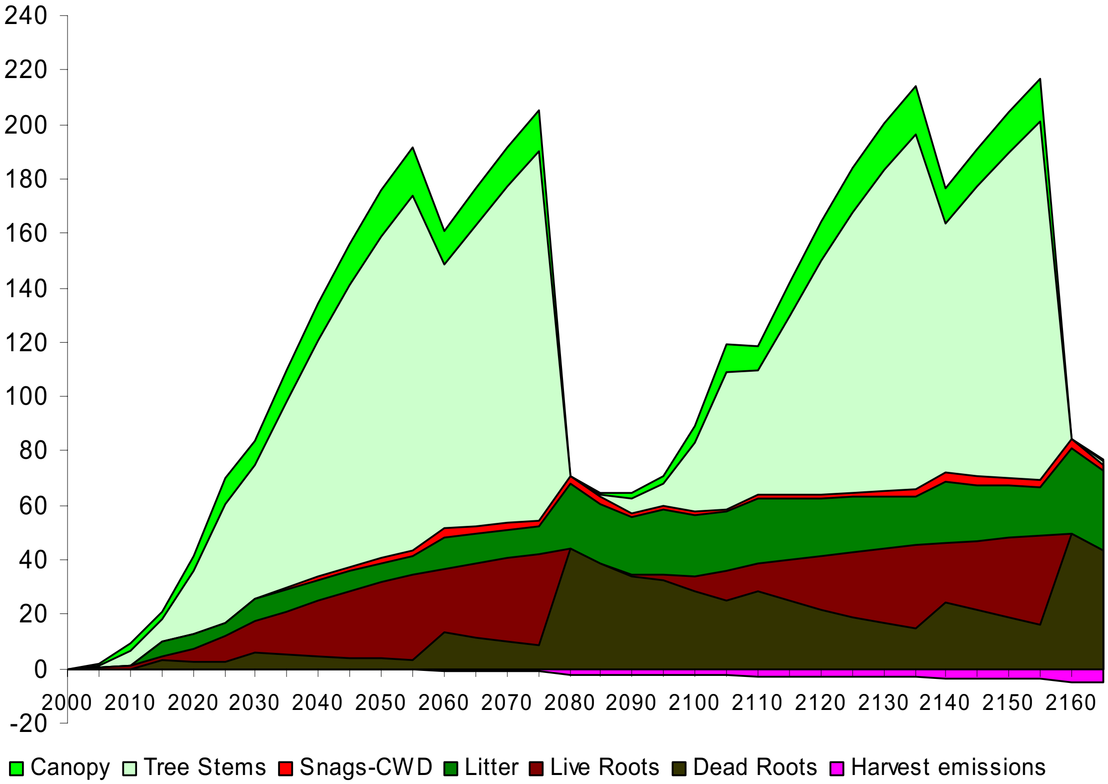

Figure 5. Forest carbon on two 80 year rotation in metric tons/ha (after Harvest).

4.1.1.3. The 120 year rotation and No Action scenarios

These two scenarios will be evaluated together in terms of their forest carbon pools. In terms of treatments, the 120 year scenario has had a PCT early in the rotation and three commercial thinnings, therefore the forest biomass and carbon pools will be significantly different. The No Action scenario should not be confused with natural stands, which are generally characterized by poor stocking and periodic disturbances within the first 120 years. The No Action scenario would be subject to a higher risk of disturbances, especially fire and diseases associated with overly dense stands.

There is 13 % more carbon in the forest pools of the No Action scenario than in the 120 year scenario, most of it accumulated in the stem and live roots, with a difference of 20 and 18 % respectively in those particular components between the two scenarios (Table 7).

Table 7. Forest carbon pools in metric tons/ ha prior to harvest in 2120, compared to a No Action scenario

	2000	2120	NA in 2120
Canopy	0.00	15.56	19.66
Tree Stems	0.00	171.59	204.82
Snags	0.00	2.04	5.52
Dead Roots	0.00	8.43	0.00
Live Roots	0.00	44.48	52.50
Litter	0.00	8.77	1.82
TOTAL	0.00	250.86	284.31

Not forgotten must be the fact that the 120 year rotation was commercially thinned three times through the scenario (ages 30, 60, 90): The No Action scenario is above the 120 year scenario at all points in time due to this fact. The No Action scenario also has more carbon in snags, which implies the effectiveness and higher productivities achieved when treatments to reduce competition are applied (Figure 6).

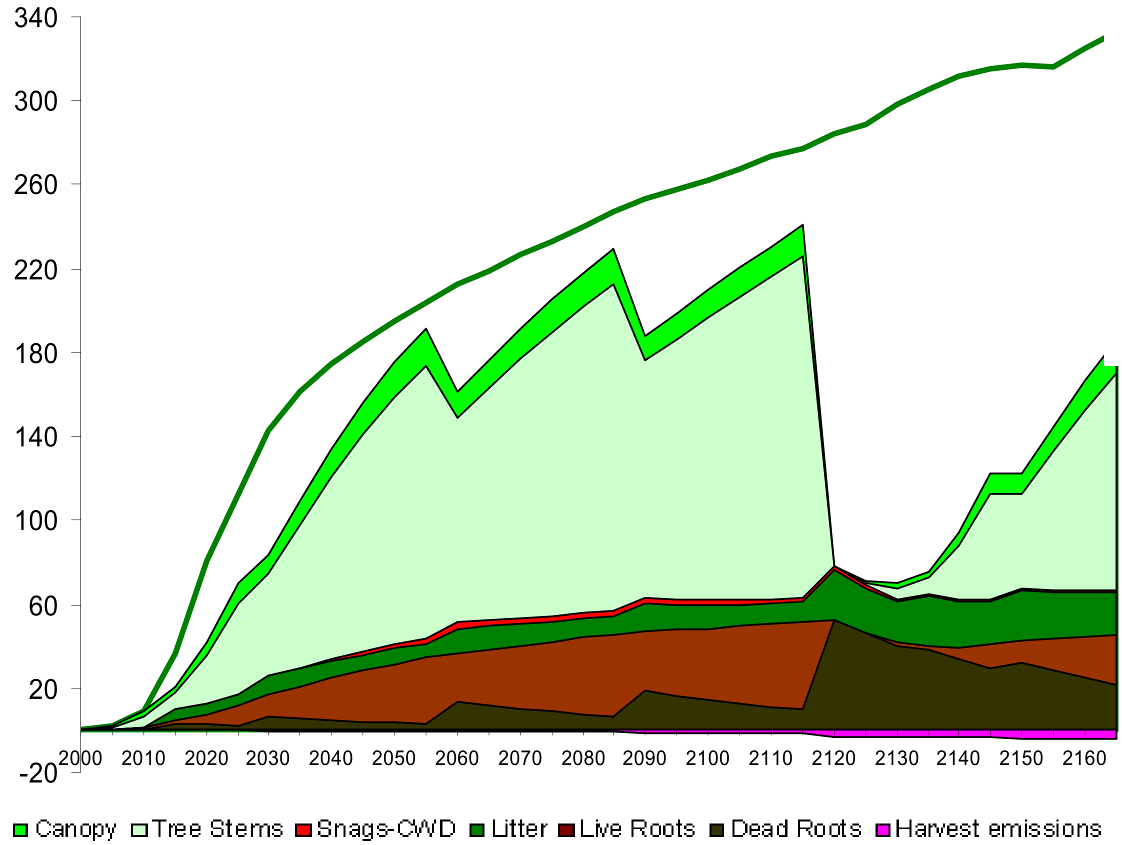

Figure 6. Forest carbon pools (after harvest in 2120) for the 120 year rotation scenario vs. No Action management scenario (No Action total forest carbon = top line).

Carbon sequestered in the live roots amount to about 18 % of the total carbon in the forest pools in the 120 year scenario, versus 19.5 % of total carbon in live roots pools for the No Action scenario. There are higher levels of carbon in the litter and dead root pools in the 120 year rotation because of the different silvicultural regime. This differentiation starts at the time of the PCT, where the growth rate for the No Action scenario is still very high. Again, most of the difference is accounted for by the commercial thinnings and the differential in the amount of trees per hectare. The No

Action scenario does not seem to have been slowed down by competition, and mortality seems very low when looking at the total carbon in the snag component and comparing that number to the snags found in the 120 year rotation, which is about half, but had four intermediate operations (PCT and 3 CT).

On a pure forest carbon basis, the No Action scenario forest pools are greater than any of the other scenarios as a consequence of the lower removals and higher overall stocking through the management period considered.

4.1.1.4. Summary forest carbon with different rotations

A summary for the carbon stored in the forest is provided on a net basis, meaning the carbon emissions coming from silvicultural operations are calculated and deducted from the total carbon pools (refer to Methods section for emission calculations). Thus, net carbon sequestered through the different scenarios is the sum of the carbon in all live and dead pools through the management period, with harvest and thinning emissions subtracted.

When considering carbon sequestered in the forest while accounting for the emissions from operations on site, the No Action scenario is above any other scenario. The 120 year scenario follows, and is slightly higher than the 80 year scenario. Last in this list is the shorter 40 year rotation.

The residual of carbon carried on from one rotation to the next in the litter, snag and root pools increases from 50 metric tons/ha to about 70 metric tons/ha in 165 years for all the rotations in which management comes into place. The results for the increase in the litter pool assume that no fire is used as a site preparation tool. Fire would volatilize much of the carbon that is considered sequestered after the harvest (Figure 7).

Carbon pools are estimated every five years, because there is not a continuous measure of the inventory in between the five year management steps simulated. In order to come up with estimates of the areas under the different curves, the total carbon in the forest pools at the beginning of each 5-year management step is multiplied times five and then added together.

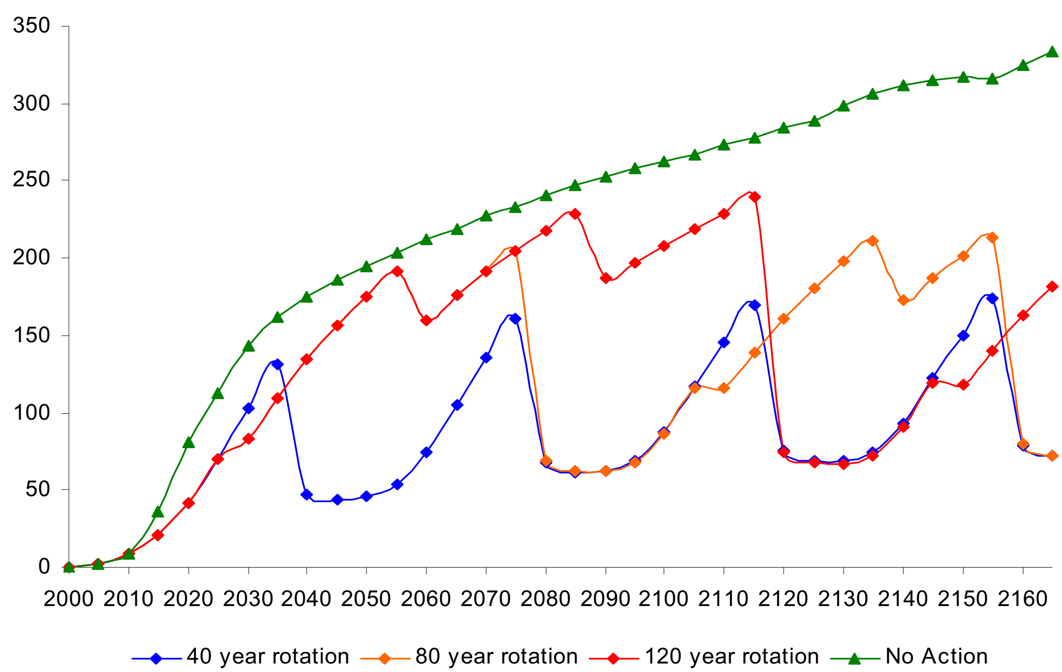

Figure 7. Net Carbon in the forest pools for all rotations through time in metric tons /ha, with emissions from operations deducted.

From these calculations, average annual carbon sequestered in the forest can be estimated for various intervals of time (Figure 8). Periods encompass forty years and do not consider the last harvest at year 40, 80, 120 or 160 to have been materialized. The Average carbon in the forest pools is the highest for the No Action scenario, for any interval of time considered.

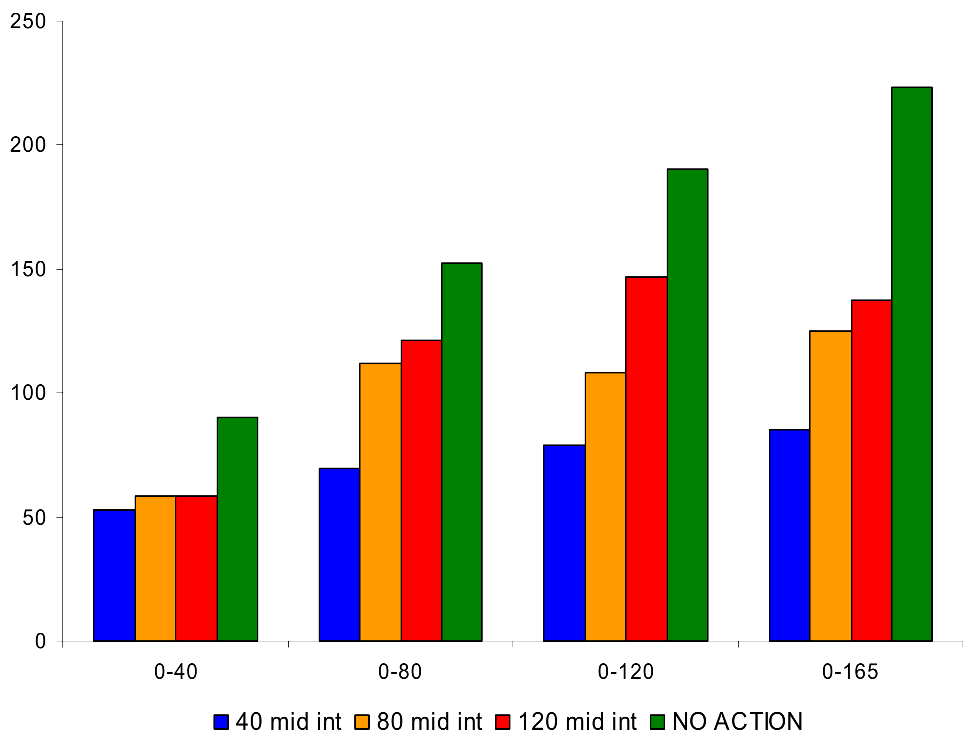

Figure 8. Average carbon in the forest pool for all rotations at different intervals of time in metric tons/ha with emissions from operations deducted

Over the total period of 165 years, the No Action scenario supports an average of 223 metric tons/ ha. As a comparison and reference, the median old growth volume as a single point estimate is 11012 ft3/ acre. The volume number was derived from the FIA riparian data and the Prime database using all unmanaged stands over 80 years in the sample (Woundenberg & Farrenkopf 1995). The median old growth volume corresponds to the volume found in year 2110 for the No Action scenario. This is to show the substantial potential differences between Old Growth and the No Action afforestation case, where on average, according to the volume estimate, and old growth stand would support about 200 metric tons/ ha on average over the same period of time.

At the other extreme is the base, the 40 year rotation, which when considering the 165 years of management sequesters an average of 85 metric tons/ha. Over this interval, the No Action scenario provides 163 % more carbon than the 40 year rotation; the 80 year rotation provides 47 % more and the 120 year rotation 62 % more carbon. These averages change somewhat depending the time interval considered. For example, during the first 80 years of management, the average carbon in the forest pools for the 40 year scenario is about 3/5 the carbon in the 80 year scenario, because the 80 year rotation has not been harvested yet. The 120 year rotation is about twice on average the carbon in the 40 year rotation when the interval in question is the first 120 years of management, and harvesting has not yet occurred.

4.1.2 The Carbon in Products

Carbon sequestered in wood products is an important pool, and its importance and relevance to the carbon story will depend on the permanence and useful life of those products. On a 165 year management scenario, there are four regeneration harvests done on the 40 year rotation, two on the 80 year rotation and a single on the 120 year rotation. Volumes harvested at the end of the rotations ranged from 5210.68 ft3 / acre for the shorter rotation to 9562.76 ft3 / acre for the longer rotation. Totals harvested, including commercial thinnings, increased this number to 15359.07 ft3/ acre for the 120 year rotation, 10935.23 ft3/ acre for the 80 year rotation. Since the 40 year rotation only had a pre commercial thinning, the total volume harvested stays the same (Table 8).

Table 8. Volumes from commercial thinning (CT) and final harvests for different rotation lengths in ft3/ acre.

	40 year rotation	80 year rotation	120 year rotation	No Action
1rst CT		816.43	816.43	
2nd CT		2127.19	2127.19	
3rd CT			2852.69	
Final Harvest	5210.68	7991.61	9562.76	
Total Volume	5210.68	10935.23	15359.07	0

In terms of total volumes harvested, the numbers are almost equal when considering time. The volume from a single 120 year rotation, 15359 ft3/ acre, is about the same as three 40 year rotations, totaling 15632 ft3/ acre. On the same track, a single 80 year rotation, 10935.23 ft3/ acre, is about the same as two 40 year rotations, 10421.36

ft3/ acre.

The volumes harvested are converted to biomass by using a standard wood density of 28.08 lbs / ft3 for Douglas-fir, and later converted to metric units to be consistent with metric tons/ ha units. The repartition of the biomass on a dry weight basis into different products and co-products in kg/ MBF of planed dry lumber is shown in Table 9 (derived from Table 1.4, App B, CORRIM 2002).

Approximately half of the biomass harvested goes to lumber, with the other half distributed among products with much shorter useful lives. Once the biomass is defined, it is turned into carbon pools using percent carbon ratios for the species (Birdsey 1992)

Table 9. Biomass distribution in kg of forests products/MBF of planed dry lumber produced.

INPUT		**OUTPUT**					
LOGS		**product**	**co-product**				
		lumber	bark	chips	shavings	sawdust	bark fuel
101 ft3 / MBF dry planed lumber	Kg/MBF	644.7	111.6	429.5	59.9	116.9	18.3

The longevity of lumber against shorter lasting products is the reason why the close to a half ratio between long and short term products in terms of biomass and carbon is not consistent with the longer rotation numbers (Table 10). The 80 and 120 year rotations have had 2 and 3 commercial thinnings respectively through the rotation, which increases the longer lasting products pool against the shorter pool that readily decomposes.

Table 10. Total products in metric tons of carbon /ha for all rotations.

Rotation Length	40 year	80 year	120 year
lumber	49.77	100.34	129.55
bark	8.08	13.33	15.76
chips	31.12	51.32	60.68
shavings	4.34	7.15	8.46
sawdust	8.47	13.97	16.52
fuel bark	1.32	2.18	2.58
Long lasting products	49.77	100.34	129.55
Short lasting products	52.01	85.77	101.42
Total Products	101.78	186.11	230.97

There are 49.7 metric tons/ha of carbon in lumber on the 40 year rotation. The 80 year rotation, through harvest and commercial thinnings, is 200 % the carbon from the lumber manufactured in the base case, at 100.3 metric tons/ha. The 120 year rotation is 260 % the carbon in lumber and 194 % the carbon in short term products from the 40 year rotation. For the short term products carbon pools, the 80 year rotation is about 164 % the amount sequestered by the 40 year rotation. No Action produces no products.

The volume trend shown in Table 9 differs from the carbon trend because of decomposition factors that are incorporated in the carbon analysis but not in the volume totals given by rotation. The carbon pools established in Table 7 are totals at the end of each rotation. The commercial thinnings for the 80 year rotation take place at years 30 and 60, which means the long and short term products obtained from those operations (about 40 % of the total volume of the rotation) have been decomposed for 50 and 20 years respectively. The same is true for the 120 year rotation, which thinnings at ages 30, 60 and 90, encompass about 38 % of the total volume from the rotation, and have been decomposed for 90, 60 and 30 years respectively.

The decomposition equation is taken from Aber and Melillo (1991)(See Methods section), and decomposition rates are 1%/year for lumber and 10%/ year as average for the short term products pool. The product pools are decomposed using a simple decay model which compared to a fixed life decay model would have a different impact on the thinning treatments and short rotation scenarios.

4.1.2.1 Carbon in Long Term Products: lumber

There are four harvests within the same period of time for the 40 year rotation compared to a single one for the 120 year rotation, therefore an analysis through time is pertinent to the overall understanding of product's trade offs in the carbon story (Figure 9 and 10).

The lumber is decomposed through time at a 1% per year. By the time of the fourth 40 year rotation regeneration harvest, the cumulative amount of carbon sequestered in lumber products is highest for the 40 year rotation, followed by the 80 and 120 year rotations. The average carbon sequestered in the lumber pool through the management scenario is highest for the 40 year rotation, with 64 metric tons/ ha followed by the 80 year rotation with 58 metric tons/ ha, or 90 %. On an average basis, the 120 year rotation sequesters in the lumber pool about 80 % of what the 40 year rotation does (Table 10). A bias exists when considering any specific interval of management for calculating the averages, therefore different intervals of time need to be addressed.

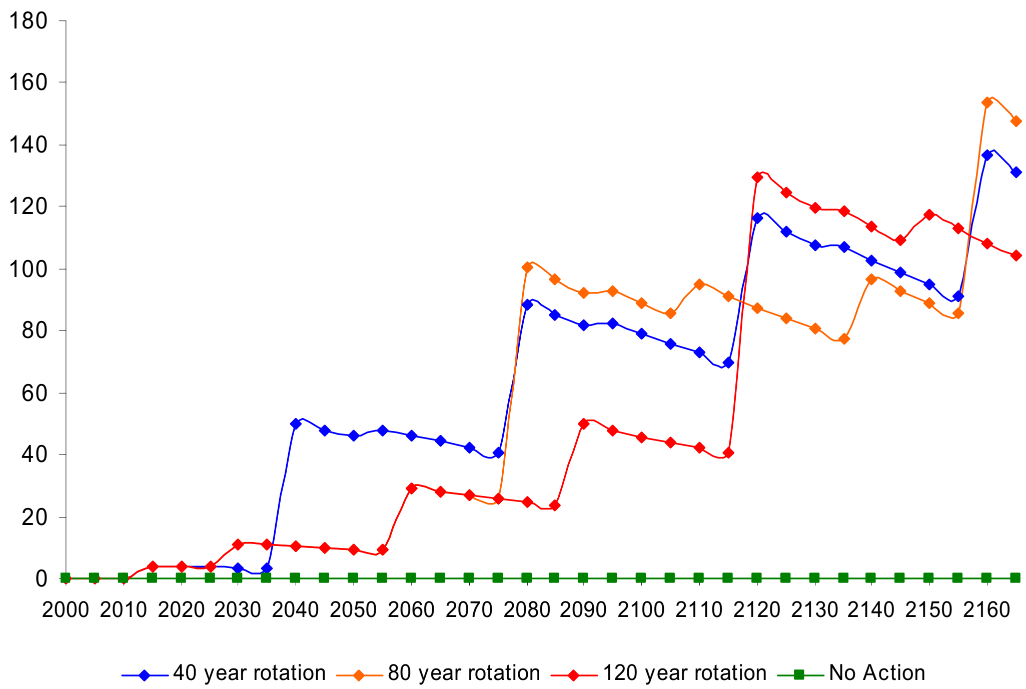

Figure 9. Long term products carbon pool in metric tons/ha of carbon for all scenarios through the 165 years of management.

4.1.2.2 Carbon in Short Term Products

The short term products pool decomposes at an average rate of 10 % per year, and essentially disappears before the next regeneration harvest for all the scenarios (Figure 10).

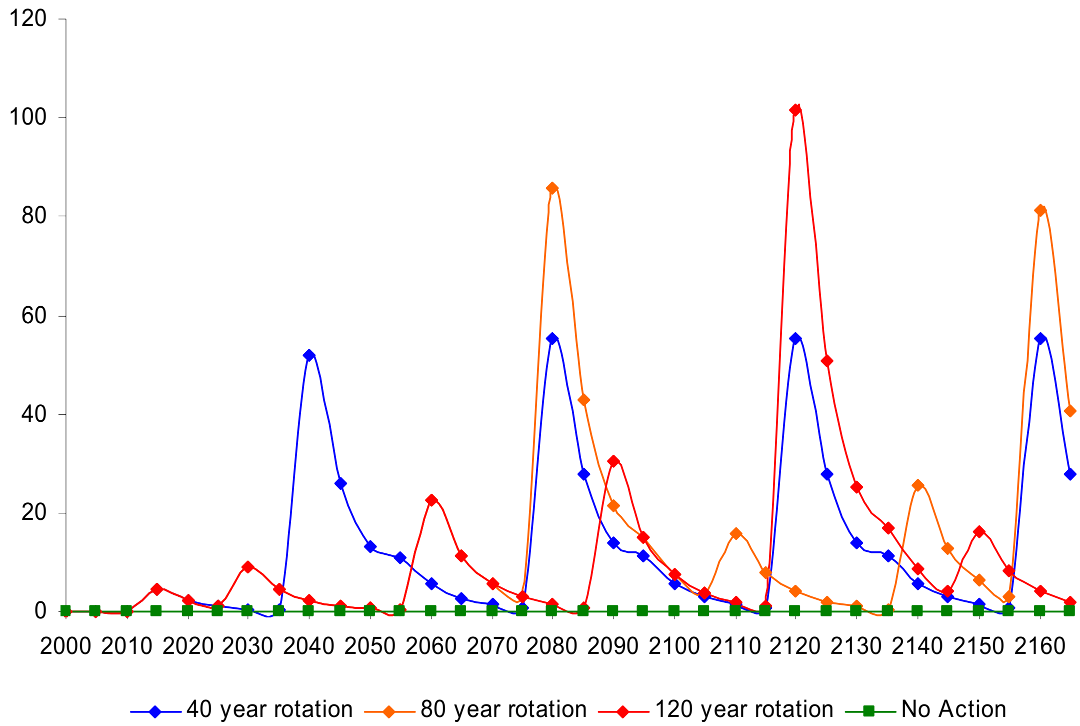

Figure 10. Short term products in metric tons/ha of carbon for all scenarios through the management cycle.

The average carbon sequestered in the short term products pool is the highest again for the 40 year rotation, followed by the 80 and the 120 year rotations (Table 11). The total amount of carbon sequestered in the short term products pool is about 20% of the lumber pool for all rotations. This percentage will increase if the number of years the material has been decomposed decreases (i.e. for the 120 year rotation, the number is 22 %). The No Action scenario sequesters nothing in products since no harvesting operations are conducted.

Table 11. Average carbon sequestered in products pool through the 165 year management cycle in metric tons /ha compared to the 40 year base. .

		Period average	Percentages
40	lumber short term products total	64.12 13.37 77.49	base
80	lumber short term products total	58.11 13.51 71.62	92 %
120	lumber short term products total	50.21 11.15 61.36	79 %

The estimated amounts of carbon sequestered in the products pools presented above are not net estimates because they do not include emissions from harvesting and manufacturing activities. The emissions are cumulative from rotation to rotation and must be deducted from the total amount of carbon sequestered to make the analysis consistent.

4.1.2.3. Carbon emissions from Forest operations and Product Manufacturing

Forest operations and manufacturing emissions are shown as negative values because they are conceptually the opposite of sequestration (Figure 11). By the time of the fourth regeneration harvest for the 40 year rotation, the 80 year rotation has accumulated 86 % of the base case harvesting emissions, and the 120 year rotation about 71 %, with periodic averages of 2.1 metric tons/ha for the 40 year scenario, 1.8 for the 80 year scenario and 1.5 metric tons/ha for the 120 year scenario through the 165 years of management evaluated (Table 12).

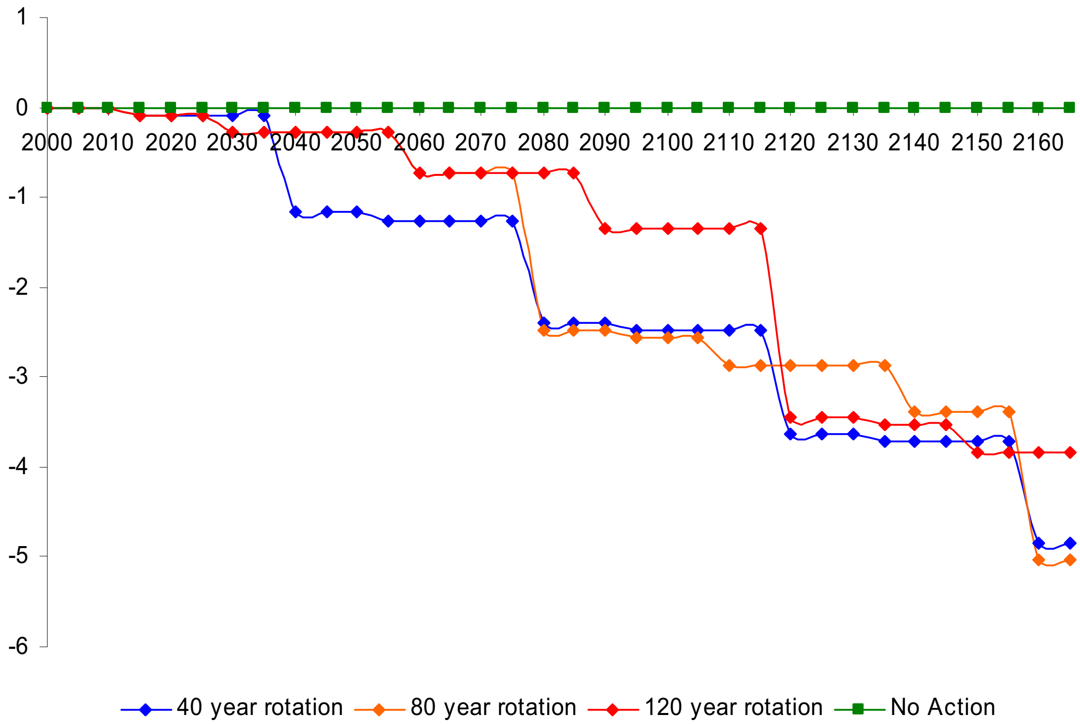

Figure 11. Forest operations emissions in metric tons of carbon/ha for all scenarios through the 165 year management cycle.

The manufacturing emissions, as expected, are also the highest for the 40 year rotation, since there are more activities prescribed through time. Manufacturing emissions are about ten times the harvesting emissions (Table 12). Periodic average manufacturing emissions for the 165 years considered, are 23 metric tons/ha for the 40 year scenario, 20 for the 80 year scenario (87 % of base) and 17 metric tons/ha for the 120 year scenario (74 % of base) (Figure 12, Table 12).

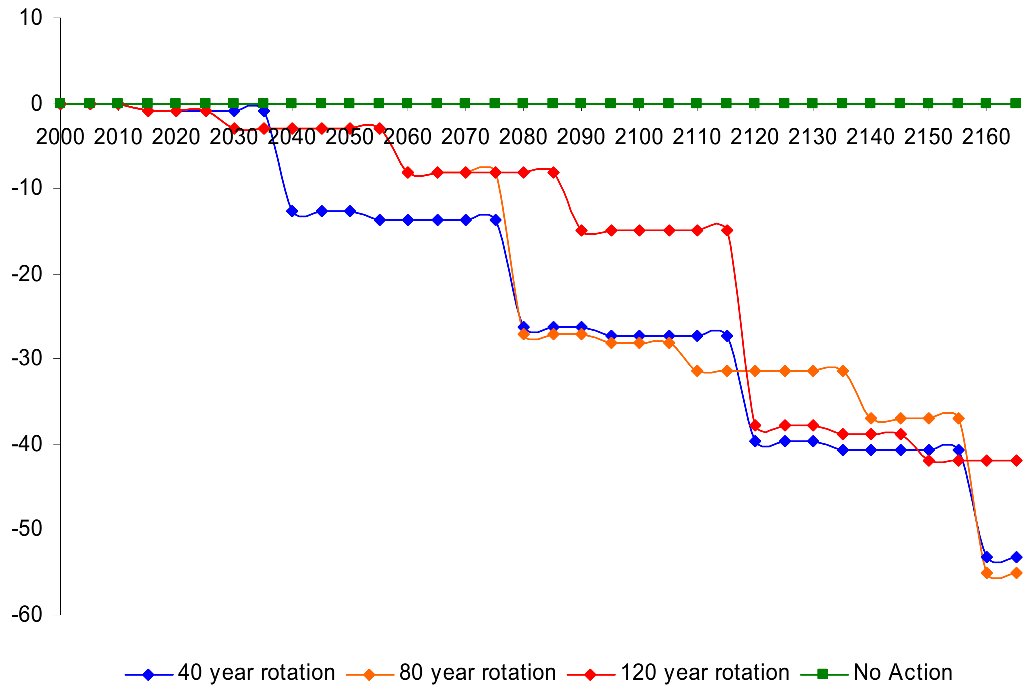

Figure 12. Manufacturing emissions in metric tons of carbon/ha for all scenarios through the 165 year management cycle.

Average total emissions through the 165 year management cycle are 25 metric tons/ha for the 40 year scenario, 22 metric tons/ha for the 80 year scenario (88 % of base) and 18 metric tons/ ha for the 120 year scenario (72 % of base). The No Action scenario produces no emissions.

Table 12. Average harvesting and manufacturing emissions for all rotation scenarios in metric tons/ha for 165 years of management.

		annual average	total
40	harvest emissions manufacturing emissions	2.09 22.88	24.97
80	harvest emissions manufacturing emissions	1.84 20.15	21.99
120	harvest emissions manufacturing emissions	1.54 16.81	18.35

We can now calculate net carbon in products by deducting the emissions from the operations throughout the scenarios.

4.1.2.4. Average net carbon in Product pools

Net product pools are the accumulation of the products pools with emissions from forest operations and manufacturing subtracted. Figure 13 shows net product pools for all rotations through the 165 years of management. The net carbon in products pools increases with each regeneration harvest, for all rotations.

The 40 year rotation sequesters more carbon than any of the other rotations, at any length of interval considered, with a net average of 53 metric tons/ha through for the 165 year management cycle.

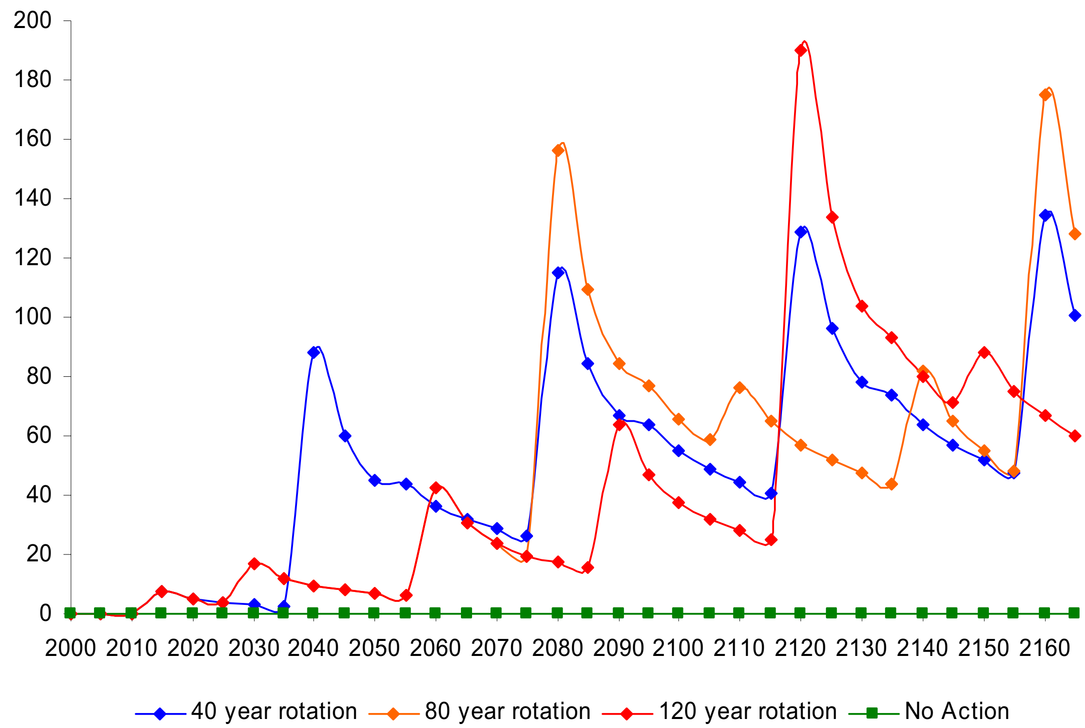

Figure 13. Net carbon in product pools in metric tons/ha for all scenarios (area under curves).

The 53 metric tons/ha for the base compared to 50 for the 80 year scenario (94 % of base) and 43 metric tons/ ha for the 120 year rotation (81 % of base), and zero for the No Action scenario (Figure 14, last interval). Periods encompass forty years and do not consider the final harvests at years 40, 80, 120 or 160 to have been materialized. The difference in average net carbon sequestration decreases with increasing years considered, because the longer intervals include more harvesting activities from the longer rotations. It is also important to note that the longer term rotations essentially differ in the entry of products. Since the volume flow into products are different for each scenario, it will be important to understand the consequences of product substitution from any shortfall in wood products.

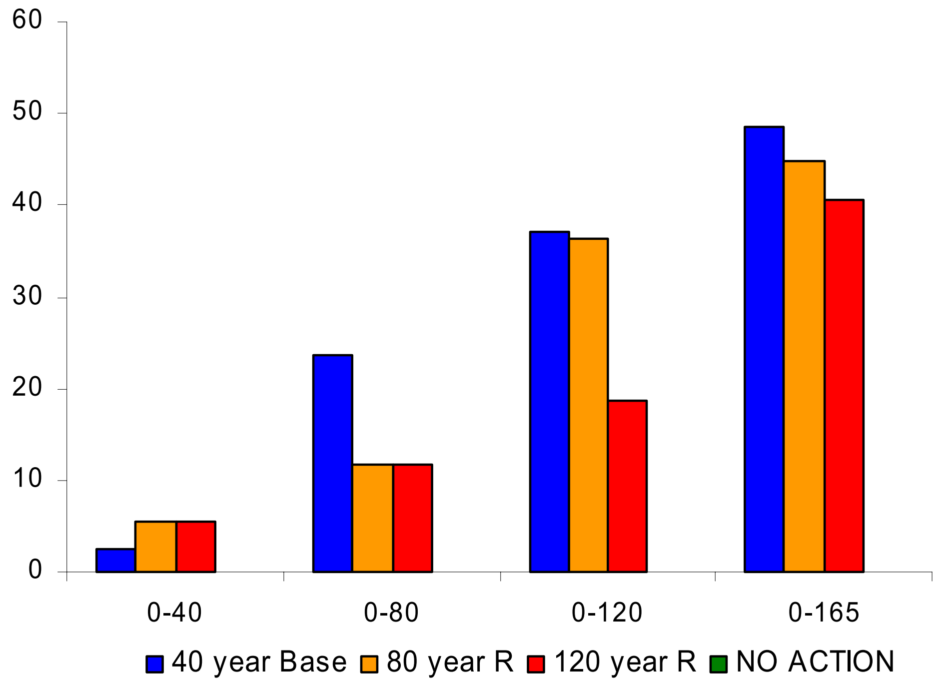

Figure14. Average net carbon sequestered in products pools at different intervals through the 165 year management cycle, in metric tons /ha.

4.1.3. The Carbon in Forest and Product Pools

The next step in the analysis of the carbon story is to evaluate the forest carbon together with the net products carbon for all the different scenarios through time (Table 13). The base case scenario sequesters the least carbon on average when evaluating the forest and products pools together, except when considering the first 40-year interval, where the average for the base is slightly higher than the 80 and 120 year rotations.

Table 13. Summary table: Net carbon averages in forest and products pools for different intervals of time through the management cycle in metric tons/ha for all scenarios.

	averages			
	0-40	0-80	0-120	0-165
40 year rotation BASE				
NET FOREST	47.19	65.82	77.25	84.71
NET PRODUCTS	2.58	23.56	37.02	48.66
NET FOREST & PRODUCTS	49.77	89.38	114.28	133.37
80 year rotation				
NET FOREST	42.07	108.05	102.84	124.35
NET PRODUCTS	5.56	11.80	36.36	44.89
NET FOREST & PRODUCTS	47.63	119.84	139.21	169.23
120 year rotation				
NET FOREST	42.07	108.05	144.32	133.60
NET PRODUCTS	5.56	11.80	18.69	40.47
NET FOREST & PRODUCTS	47.63	119.84	163.01	174.07
No Action				
NET FOREST	68.21	137.30	178.19	213.32
NET PRODUCTS	0.00	0.00	0.00	0.00
NET FOREST & PRODUCTS	68.21	137.30	178.19	213.32

Forest carbon increases with longer rotations and longer intervals while forest products carbon decreases. The No Action scenario forest carbon for the 165 year interval is 60 % higher than the base, with forest and products considered. The 120 year rotation is 30 % higher and the 80 year rotation is 27 % higher (Figures 15 and 16).

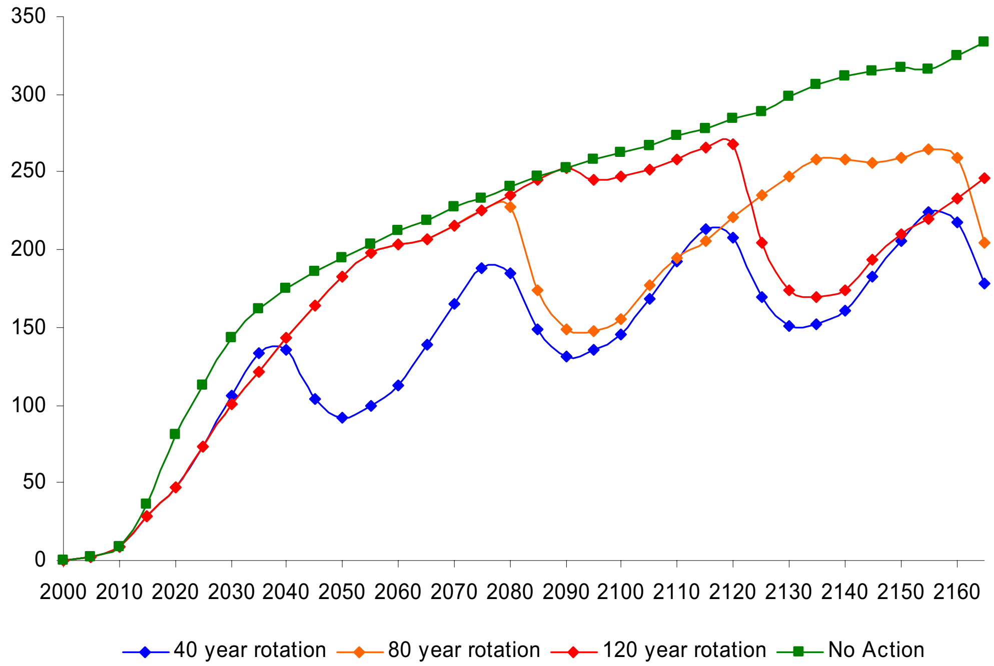

Figure 15. Net carbon sequestered in the forest and products pools in metric tons / ha for all scenarios through the management cycle (area under the curves).

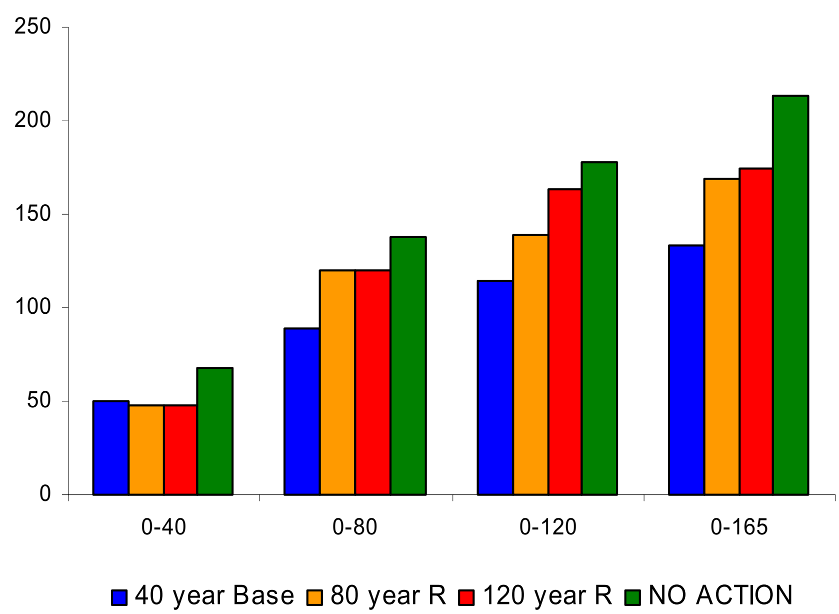

Figure 16. Net average carbon sequestered in the forest and products pools at different intervals of time within the 165 years of management in metric tons/ha.

The cumulative net products pool for the 40 year rotation reduces the total carbon losses for the short rotation over time but total carbon is still lower than any of the other rotations through the 165 year period (Figure 15 vs. Figure 7 and Figure 16 vs. Figure 8).

4.1.4. Carbon displacement

Carbon displacement, the carbon not emitted from fossil fuels when wood is used to produce energy, although conceptually important, does not change the numbers and generals patterns observed previously among rotations, due to efficiency differences between wood and fossil fuel burners.

The displacement of fossil fuel based energy by bioenergy increases with time because the displacement of fossil fuels by renewable resources is permanent and cumulative through time. Furthermore, displacement is equivalent to avoided emissions, therefore considered sequestration in the spectrum of this analysis.

The percentage of short lived co-products that are used for energy will vary with the economic allocations of those products relative to their value as energy. In some cases most of the co-products volume will be used as energy and in other cases very little. Co-products not used as energy are generally allocated their share of the harvest and manufacturing emissions burden.

For this simulation and evaluation of the carbon displacement, the maximum possible displacement impact is developed by burning all of the co-products for their energy value in a wood boiler. This is an extreme case, to consider all short term products as hog fuel, since some of these products have a more valuable usage, such as engineered wood. The manufacturing emissions are burdened for the usage of the short term products as energy (see Methods).

The 40 year rotation displaces 38 metric tons/ha per year of carbon by using less fossil fuels for energy, the highest of the scenarios. It is followed by the 80 and 120 year scenarios, with averages of 33 and 28 metric tons/ ha respectively (87 and 74 % of the base respectively). The No Action scenario displacement is zero since no harvesting has occurred (Figure 17).

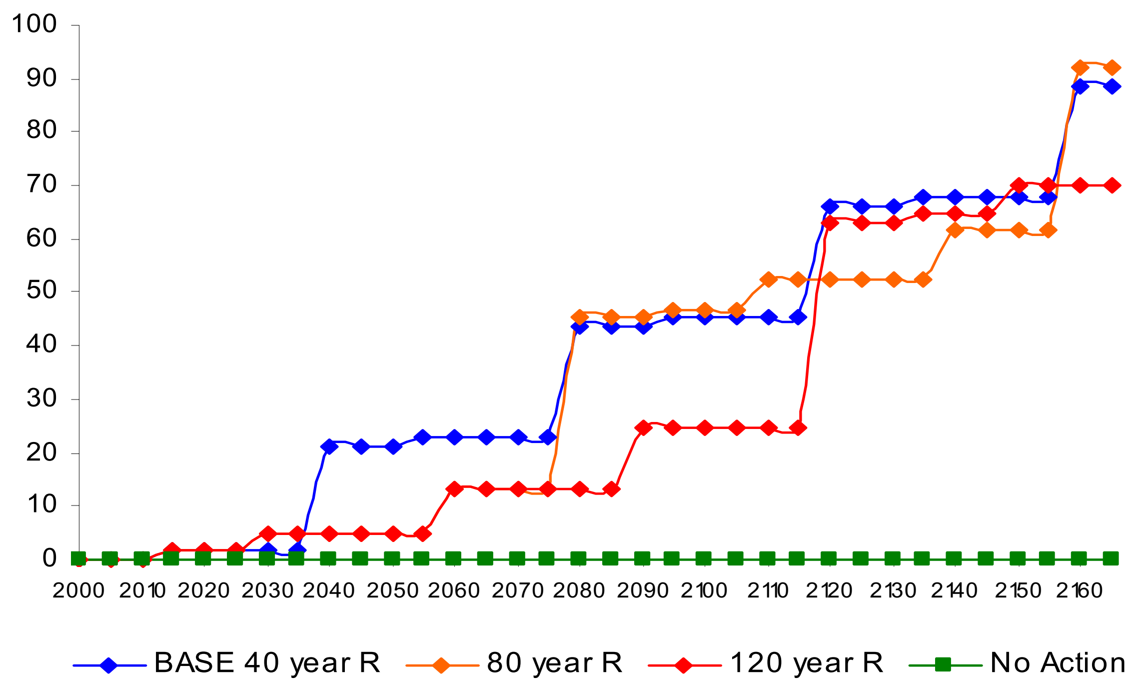

Figure 17. Carbon displacement from fossil fuel based energy by bioenergy in metric tons/ha through time using all of the short term products as hog fuel.

When incorporating the carbon displacement into the overall carbon story, the benefits of using wood instead of fossil fuels can only be appreciated when longer intervals of time are considered (above 120 years)(Table 14).

Table 14. Summary Table: Average carbon in forest, products and displacement for scenarios intervals through the 165 years of management in metric tons/ha.

	averages			
	0-40	0-80	0-120	0-165
40 year rotation BASE				
NET FOREST	47.19	65.82	77.25	84.71
NET PRODUCTS	2.58	23.56	37.02	48.66
NET FOREST & PRODUCTS	49.77	89.38	114.28	133.37
NET FOREST, PROD, DISPLAC.	49.44	90.05	120.28	145.82
80 year rotation				
NET FOREST	42.07	108.05	102.84	124.35
NET PRODUCTS	5.56	11.80	36.36	44.89
NET FOREST & PRODUCTS	47.63	119.84	139.21	169.23
NET FOREST, PROD, DISPLAC.	46.26	119.46	141.78	178.66
120 year rotation				
NET FOREST	42.07	108.05	144.32	133.60
NET PRODUCTS	5.56	11.80	18.69	40.47
NET FOREST & PRODUCTS	47.63	119.84	163.01	174.07
NET FOREST, PROD, DISPLAC.	46.26	119.46	165.31	181.23
No Action				
NET FOREST	68.21	137.30	178.19	213.32
NET PRODUCTS	0.00	0.00	0.00	0.00
NET FOREST & PRODUCTS	68.21	137.30	178.19	213.32
NET FOREST, PROD, DISPLAC.	68.21	137.30	178.19	213.32

Displacement is equivalent to long term storage and accumulated from rotation to rotation. The lower levels of efficiency in wood boilers when compared to fossil fuel burners reduces the displacement impact compared to long lived products but does not decay like long live products. It takes a number of rotations to accumulate in displacement more than the carbon accumulated on average in the short term products. The relative comparisons between rotations however, are not substantially different when evaluating displacement together with the other carbon pools, with the No Action scenario still sequestering more carbon than any of the other scenarios where harvestings have been done, in the interval of times considered.

When considering the entire 165 years of management, the carbon in the No action scenario is about 47 % higher than the base, the 40 year rotation, compared to a 60 % higher when displacement was not considered. Displacement is a significant positive contributing factor if enough time is considered, in this particular case, about 120 years of management are needed to observe its benefits in terms of carbon displacement.

The average carbon sequestered by the 40 year rotation when considering displacement in the long term of the 165 year management considered, is about 10 % higher than when displacement does not take place (Figure 18 vs. Fig 15, Table 14).

For the 80 year rotation it is slightly higher than 5 % more and for the 120 year rotation about 4 %. However, the base case still sequesters less carbon on average than the other rotations. The differences are smaller, with the differentials in terms of average carbon sequestration among rotations, decreasing as the analysis moves from the forest, to the products, to the potential displacement.

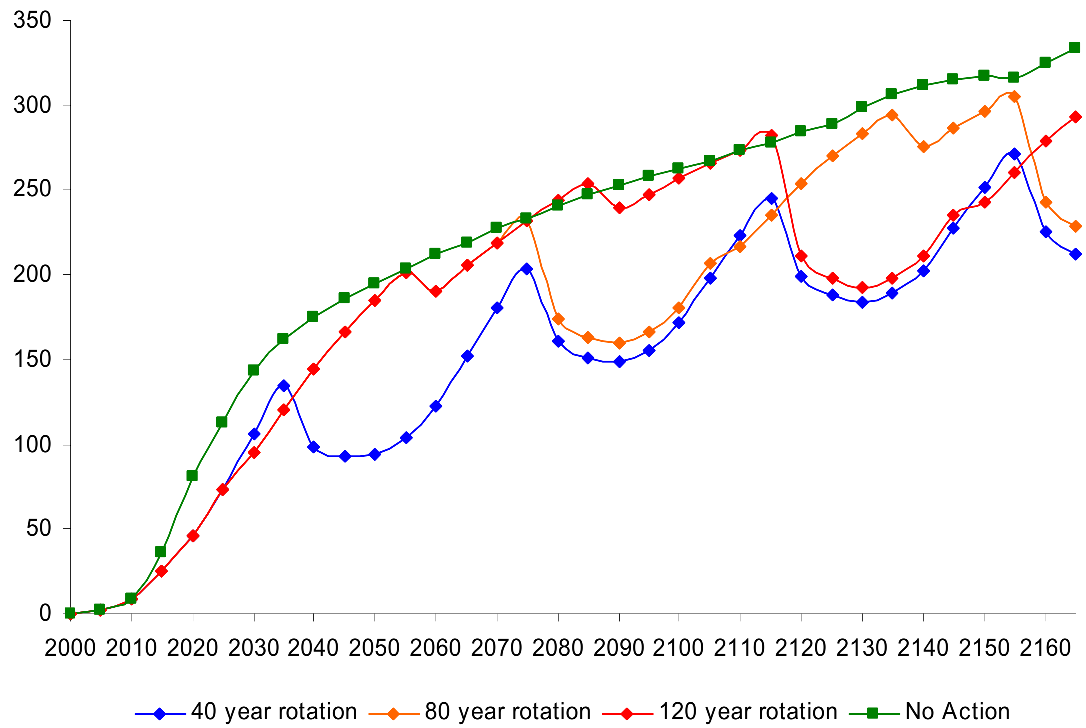

Figure 18. Net forest, products and displacement carbon pools for all scenarios in metric tons/ha accumulating through the 165-year management period.

4.1.5. Carbon substitution

The environmental analysis framework adopted by CORRIM (2002) characterizes all inputs and outputs associated with a residential building unit. Since the management alternatives consider raw material production changes, substitution of materials is implied when managing a fix number of hectares through different rotations while producing the same type of end products.

Number of potential wood framed houses from harvested volumes per hectare ranges from 4 for the first 40 year rotation, which means -3 steel framed houses, to up to 9 wood framed houses for the 120 year rotation scenario, implying -8 steel houses built, with the differential in carbon emissions associated with this different type of construction (Table 15).

Table 15. Changes in the number of steel and wood framed houses resulting from harvesting activities or lack of through time on a per hectare basis.

	2000	2040	2080	2120	2160	2165
40 year rotation						
wood framed	-1.17	**4.39**	**4.72**	**4.72**	**4.72**	-1.17
steel framed	2.17	**-3.39**	**-3.72**	**-3.72**	**-3.72**	2.17
80 year rotation						
wood framed	-1.17	-1.17	**7.86**	-1.17	**7.38**	-1.17
steel framed	2.17	2.17	**-6.87**	2.17	**-6.38**	2.17
120 year rotation						
wood framed	-1.17	-1.17	-1.17	**9.64**	-1.17	-1.17
steel framed	2.17	2.17	2.17	**-8.64**	2.17	2.17
No Action						
wood framed	-1.17	-1.17	-1.17	-1.17	-1.17	-1.17
steel framed	2.17	2.17	2.17	2.17	2.17	2.17

The net forest and products carbon sequestered in the base (40 year rotation) through the 165 years considered represents the baseline for the substitution analysis. The blue line in Figure 19 is this base line. Any shortage of wood provided in the other scenarios result in steel houses substituted with the carbon emissions then deducted from the previously derived carbon storage in forest and product pools (Figure 19).

The carbon story is much different when addressing issues pertinent to substitution. In 2040, the first harvest takes place in the base case scenario, and since there is no wood harvested in any of the other scenarios, steel displaces wood at that particular point in time for those scenarios. The 80 year rotation slightly surpasses the base case in year 2080, when both the 40 and the 80 year rotation are harvested, and it will stay higher until the 40 year rotation goes through its third harvest.

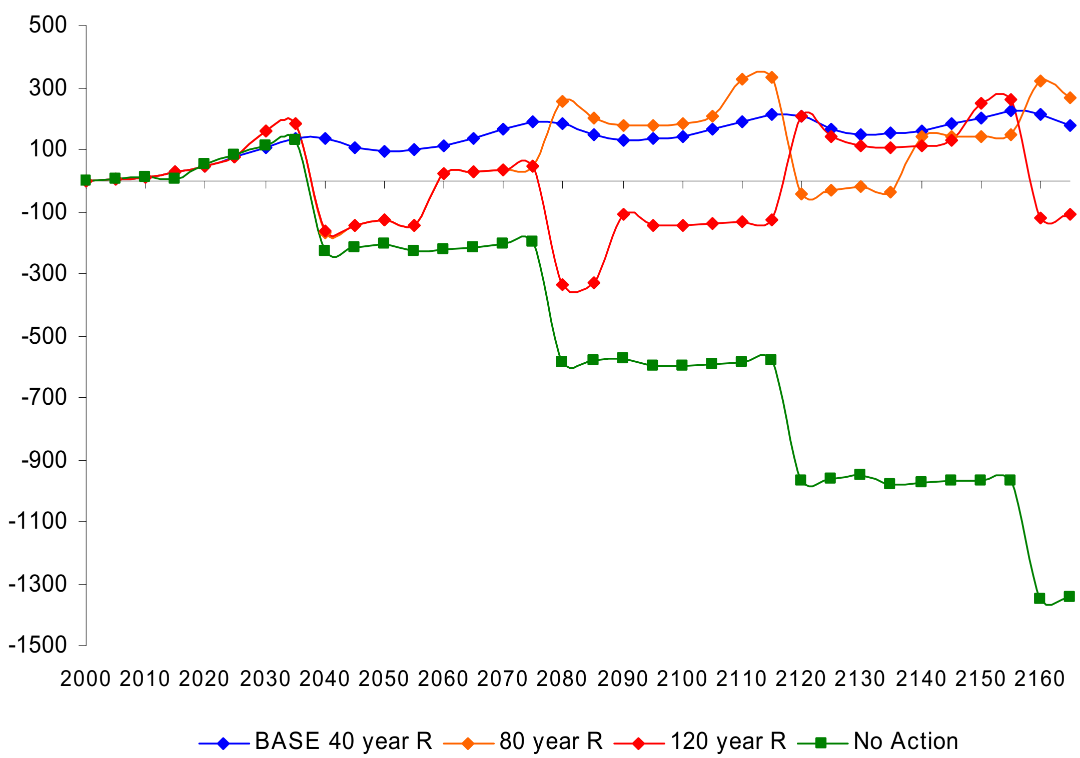

Figure 19. Net carbon substitution for all scenarios through the 165- year management period against the Base 40-year rotation, in metric tons/ ha of carbon sequestered showing trade offs between steel and wood design construction.

There is a thinning in 2110 that brings the 80 year scenario even further above the 40 year rotation base case, but this trend is reversed at the time of the third 40 rotation harvest in 2120. Throughout this time, because there has been no management in the No Action scenario, the substitution effect makes the emissions go higher, reaching 1400 metric tons/ ha of emissions by the end of the management period of 165 years.

The substitution trade offs are readily observed when the base case, the 40 year scenario, is normalized to zero (Figure 20).

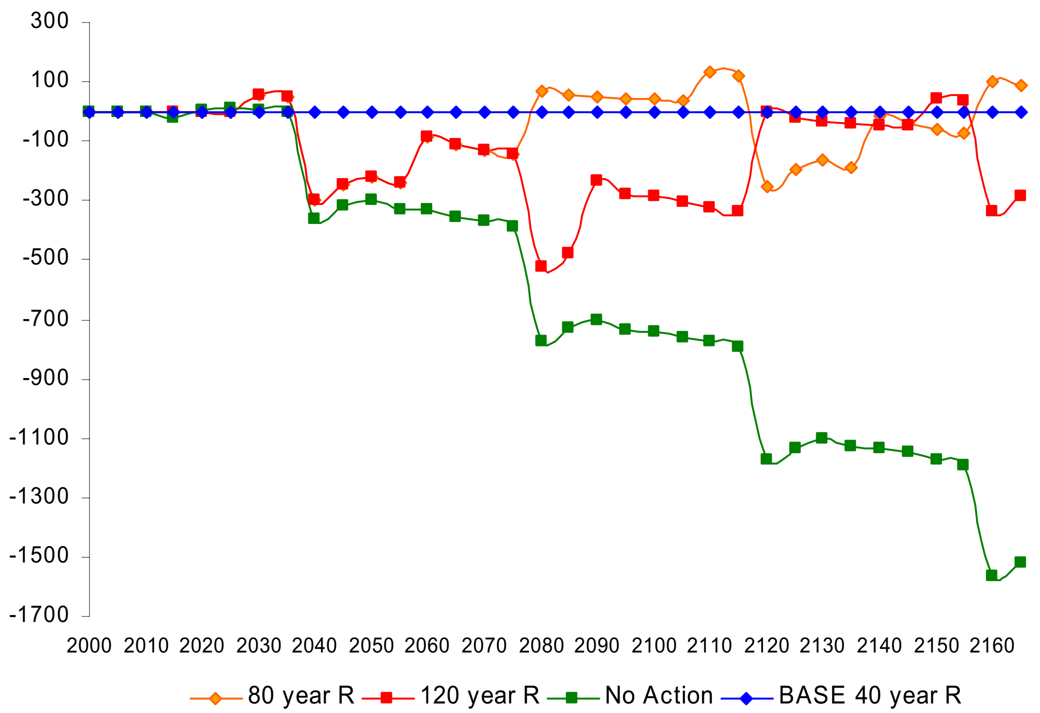

Figure 20. Net carbon substitution for all scenarios through the 165- year management period against the Base 40-year rotation normalized to zero, in metric tons/ ha of carbon sequestered showing trade offs between steel and wood design construction.

The negative numbers in the scenarios shown below illustrate the effect of allowing fossil intensive products to substitute for wood in construction. Over a long period of time, the longer rotations reduce the rate of substitution ultimately producing a surplus of wood products somewhere beyond 200 years. The No action scenario emissions are higher because the benefit of high forest carbon is more than offset by the amount of fossil fuel energy needed for construction with steel when wood is not available. The No Action scenario is followed by the 120 year scenario, for which thinnings and final harvest in year 2120 are not enough to maintain positive levels of sequestration. The 80 year scenario is the closest to the 40 year base scenario, although still sequestering less carbon for any interval considered within the 165 years.

Looking at average carbon sequestration numbers once the substitution factor has been incorporated into the carbon story changes the patterns dramatically, effectively reversing it (Table 16).

With the substitution, the shortest rotation produces the highest average levels of sequestration for all intervals, ranging from 67 to 140 metric tons/ha on average, depending upon the interval. The 80 year rotation is sequestering carbon for every interval considered, although much less than when substitution trade offs are left out. The 80 year rotation, on average, sequesters half the amount of carbon through the 165 years considered when addressing substitution. In this same interval of time, the 80 year rotation sequesters on average about 40 % less carbon than the base case.

Table 16. Summary table: Average carbon sequestration in forest, products and substitution for all scenarios through the management period in metric tons/ha.

	averages 0-40	0-80	0-120	0-165
40 year rotation BASE				
NET FOREST	47.19	65.82	77.25	84.71
NET PRODUCTS	2.58	23.56	37.02	48.66
NET FOREST & PRODUCTS	49.77	89.38	114.28	133.37
NET FOREST, PROD, DISPLAC.	49.44	90.05	120.28	145.82
NET FOR, PROD, DISPLAC, SUBST.	49.77	89.38	114.28	133.37
80 year rotation				
NET FOREST	42.07	108.05	102.84	124.35
NET PRODUCTS	5.56	11.80	36.36	44.89
NET FOREST & PRODUCTS	47.63	119.84	139.21	169.23
NET FOREST, PROD, DISPLAC.	46.26	119.46	141.78	178.66
NET FOR, PROD, DISPLAC, SUBST.	63.04	3.16	79.67	81.07
120 year rotation				
NET FOREST	42.07	108.05	144.32	133.60
NET PRODUCTS	5.56	11.80	18.69	40.47
NET FOREST & PRODUCTS	47.63	119.84	163.01	174.07
NET FOREST, PROD, DISPLAC.	46.26	119.46	165.31	181.23
NET FOR, PROD, DISPLAC, SUBST.	63.04	3.16	-58.76	-6.74
No Action				
NET FOREST	68.21	137.30	178.19	213.32
NET PRODUCTS	0.00	0.00	0.00	0.00
NET FOREST & PRODUCTS	68.21	137.30	178.19	213.32
NET FOREST, PROD, DISPLAC.	68.21	137.30	178.19	213.32
NET FOR, PROD, DISPLAC, SUBST.	38.99	-116.10	-291.21	-494.25

The 120 year scenario on average allows fossil fuels to emit almost 7 metric tons/ha through the 165 years of management. The No Action scenario difference between what it sequesters in the forest and the fossil fuels used instead of wood is equivalent to emitting 496 metric tons/ha on average through the 165 years considered, compared to 223.43 metric tons/ha of carbon sequestered on average through the same period of time when only considering the forest carbon (Figure 21).

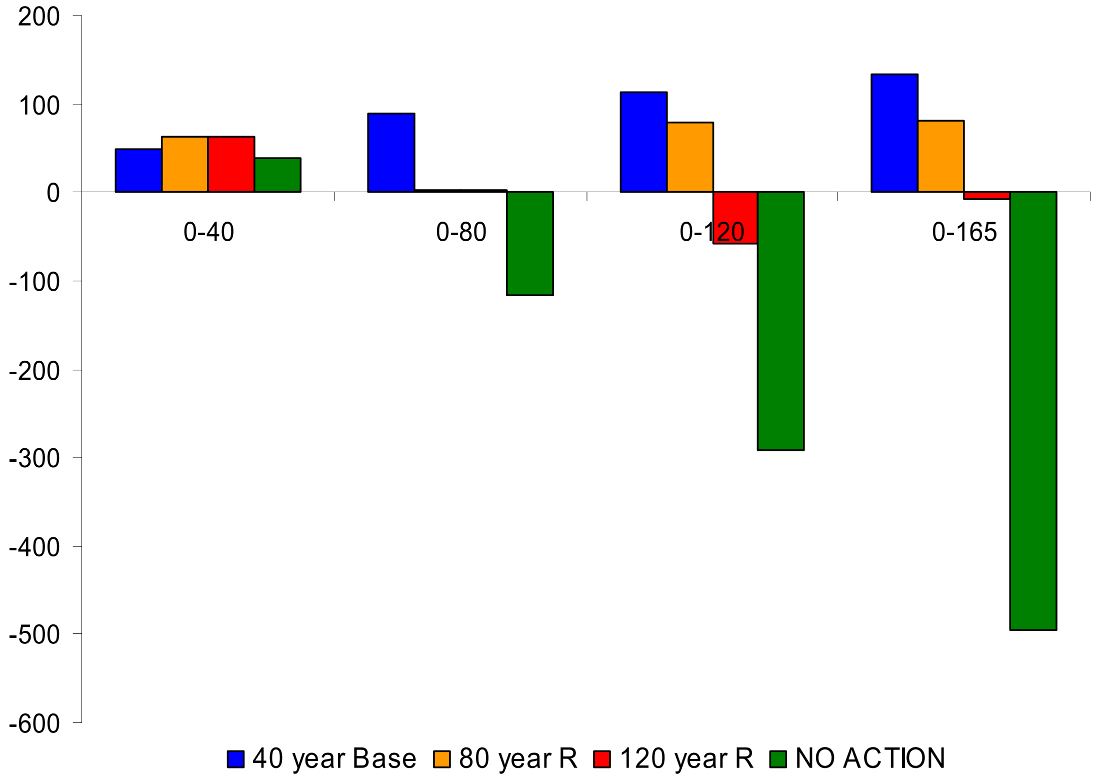

Figure 21. Average periodical sequestration for all scenarios at different intervals in metric tons /ha.

The No Action scenario sequesters the most carbon when only the carbon in the forest, products and displacement are considered, but contributes substantial emissions once substitution is included in the analysis. The 40 year rotation produced the lowest levels of forest carbon sequestration but with the addition of products and substitution it produces the least emissions, reflected in greater sequestration.

4.1.6. The Economics of the Rotation case

Soil expectation value (SEV) is calculated for the rotations previously discussed. SEV is a forestry term used to describe “the present net worth of bare forestland for timber production calculated over a perpetual series of timber crops grown on that land” (Davis and Johnson 1986). Maximizing SEV is a means to guide an investment, by identifying the management alternative with the greatest economic benefit.

All tree costs are included in the analysis, the guiding interest rate reflects the context of the Pacific Northwest, and the prescription for each scenario will be repeated over each rotation. The SEV calculations are based on Faustmann (1849). Results from calculations of SEV for the scenarios evaluated previously are presented in Table 17. Cost assumptions for these calculations are presented on Table 18.

Depending upon the owner’s objectives, the return might not be high enough to allow for the increased risks of disease or other disturbances that may impact longer rotation scenarios. The 40 year rotation has the highest SEV therefore if the sole objective was to maximize the economic return, this would be the scenario to follow.

Table 17. SEV for all rotations following assumptions cited in Table 18.

	SEV (in dollars)
40 year rotation	$463
80 year rotation	$39
120 year rotation	-$153

Table 18. Assumptions and costs for the calculation of SEV in the PNW rotation case analysis.

Case Study Variables			Planting	$263.34
	Interest Rate:	5%	Fertilizer	$45.00
	Annual Costs ($/ac/yr):	$12.00	PCT	$62.34
	Logging Cost Schedule ($ / Mbf):			
DBH	Thin Ground	Thin Cable	CC Ground	CC Cable
6	$250	$349	$215	$264
7	$238	$337	$205	$252
8	$226	$325	$195	$240
9	$214	$313	$185	$228
10	$202	$300	$175	$216
11	$191	$280	$163	$204
12	$182	$260	$150	$190
13	$174	$240	$140	$175
14	$166	$220	$130	$155
15	$158	$195	$125	$150
16	$150	$180	$120	$145
17	$145	$175	$118	$140
18	$140	$158	$114	$135
19	$135	$153	$112	$131
20	$130	$150	$110	$128
21	$129	$149	$109	$126
22	$128	$148	$108	$124
23	$127	$147	$107	$123
24	$126	$146	$106	$122
25	$126	$146	$105	$122
26	$126	$145	$105	$120

4.2. Management Intensity Alternatives

The base case for the management intensity analysis is the same 40 year scenario used for the Rotation Case. A total of 3 scenarios encompassing two prescriptions and two rotation lengths are compared. The goal is to evaluate trade offs in carbon build up and economics associated with changes in management intensity. In particular, does increased thinning and fertilization store more carbon with what economic impact? And does adding ten more years of growth sequester more carbon and with what economic effect?

There are two stands and two intensities of management in question. Both stands are planted in year 2000 with 1900 Douglas-fir trees per hectare (770 TPA). The base case stand has a site index of 110 (King, 1966), and the only silvicultural treatment is a pre commercial thinning at age 15 to 680 trees per hectare (275 TPA).

The high intensity management stands are assumed to be fertilized twice, at age 20 and 30. The silvicultural treatments associated with the high intensity management are: a pre commercial thinning at age 15 to 680 trees per hectare (275 TPA), followed by a commercial thinning at age 30 which removes slightly less than a third of the basal area (to 90 ft2/ acre). The stand is simulated as having a site index of 122 as consequence of the management treatments.

Changing the site index is the best way to model the impacts in the growth associated with fertilization practices in a simulation (McCarter, April 25th 2002). Growth projections were simulated for the base and the high intensity to 40 year rotations, growing the high intensity case to a 50-year rotation is also evaluated. Questions of interest relate to the assessment of trade offs in terms of carbon and costs: the economics associated with a higher intensity of management and slightly longer rotations. In particular, is the additionality between the two prescriptions worth the time and the investment?

The economic optimization assessment will be examined first, followed by the carbon analysis at the forest, products, displacement and substitution levels.

4.2.1 The Economics

The same methods used in the Rotation case are used in this economic evaluation for the Intensity case, with the same assumptions from Table 18. All treatment costs are included in the analysis, and an interest rate of 5 % is used to provide SEV comparisons. The prescription for each scenario includes the costs of a pre commercial thinning for the mid intensity base case, and the costs of a pre commercial and commercial thinning with two fertilizations for the high intensity case. The same prescription will be repeated over time to calculate the SEV. Results from calculations of SEV are presented in Figure 22.

The economics look best for the 40 year rotation with high intensity management, with an SEV of $487, or about 5 % more than the base, with an SEV value of $463. The 50 year rotation high intensity is about 87 % of the base case SEV. Despite these differences, in general terms the economics are relatively insensitive to the different intensity management strategies and the extension of the rotation for a few years.

On the other hand, when looking at longer rotations, the SEV value is dramatically lower, with the 80 year rotation having a value of $39 (8 % of the base SEV), and the 120 year rotation a - $159 SEV value.

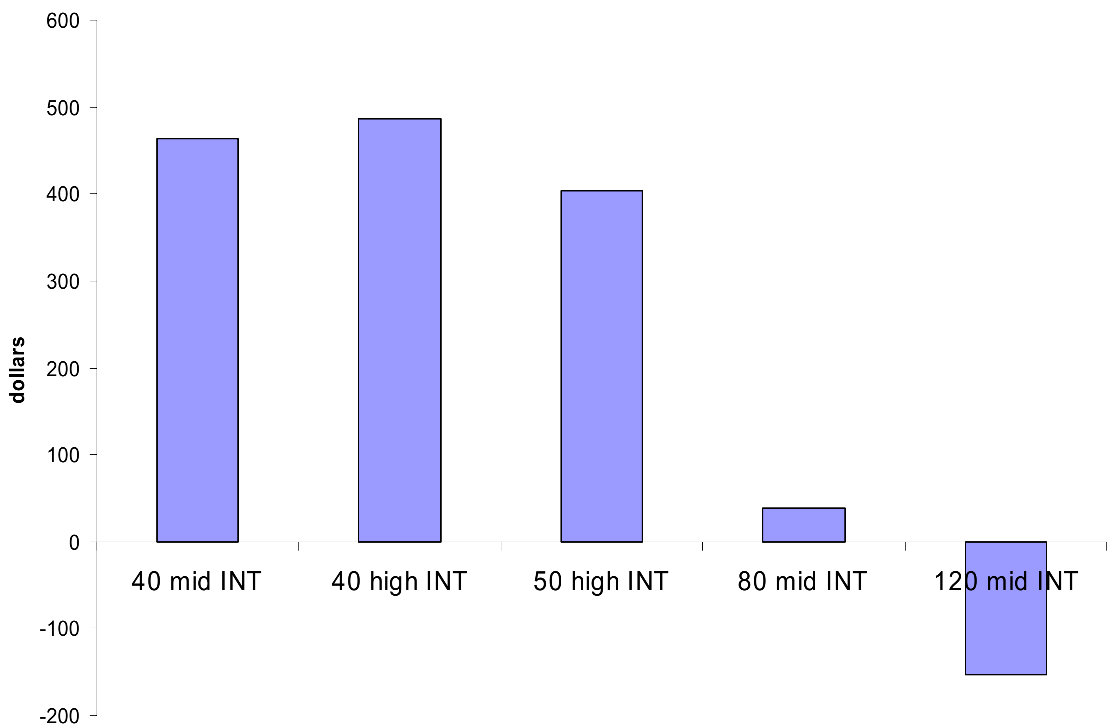

Figure 22. Soil Expectation Value (SEV) for all intensities and all rotations in dollars.

The carbon storage for the three different intensity cases adds insight into potential benefits. Is the best economical strategy also best on a carbon sequestration basis, or where are the greater gains and through what economic loss (cost) do we get the greatest storage?

4.2.2. The Forest Carbon

Since it is an afforestation case, the starting point is assumed to be zero in terms of carbon at the sites in year 2000, the beginning of the management cycle.

Table 19. Summary of carbon pools for the forest components in metric tons per hectare for the three management prescriptions.

	40 BASE	40 high INT	50 high INT
Canopy	16.80	14.22	16.98
Tree Stems	105.01	91.93	122.89
Snags	1.73	1.14	2.32
Dead Roots	1.57	5.71	4.37
Live Roots	24.32	21.42	29.27
Litter	5.07	8.68	7.91
TOTAL	154.49	143.10	183.74

When looking at the forest carbon at the end of the rotation (Table 19), the high intensity management scenario has 11.4 metric tons/ ha (or about 7 %) less carbon than the base case. Most of this difference might be attributable to the commercial thinning. Ten more years of growth under the intensive management regime are equivalent to 40 more metric tons/ha of standing carbon by the end of the rotation, an 18% increase from the base case scenario. The biggest difference among scenarios is found in the stem component, followed by dead roots and litter. The amount of litter is between 3 to 6 % of the forest carbon, but will increase considerably after harvesting, when most of the canopy is assumed to be left scattered on site. The pools that grow the fastest are the stems and the roots in all cases, exemplified below by the 40 high intensity management forest carbon distribution among components (Figure 23).

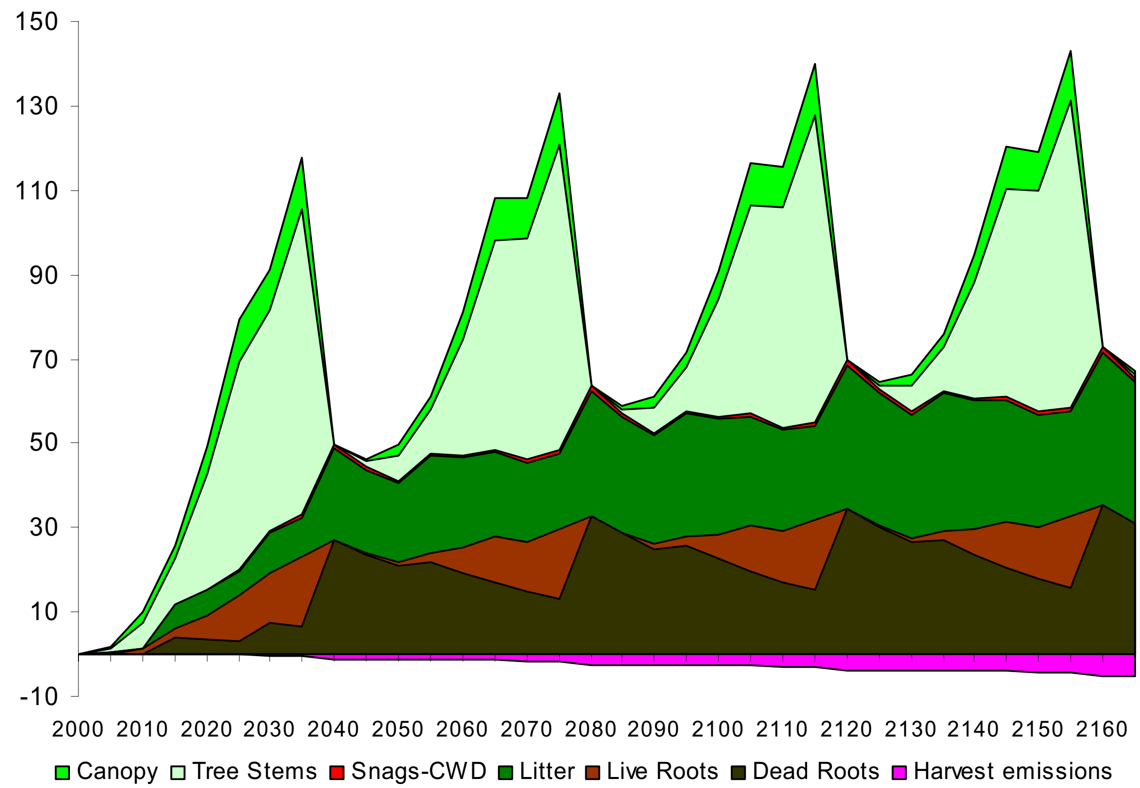

Figure 23. Forest carbon in metric tons/ha through time for the 40 year rotation high intensity management case.

Forest biomass at the end year of the rotation is not shown because harvest is assumed in 2040, therefore in 2040 there is no standing forest, it has been harvested. The litter build up can be appreciated both in 2015 after the pre commercial thinning, and later in 2030, with the commercial thinning. Regeneration harvest takes place every 40 years, and it is the building block of the forest floor carbon.

Net forest carbon (forest operation emissions subtracted) for all intensities is shown in Figure 24, as the area under the curves.

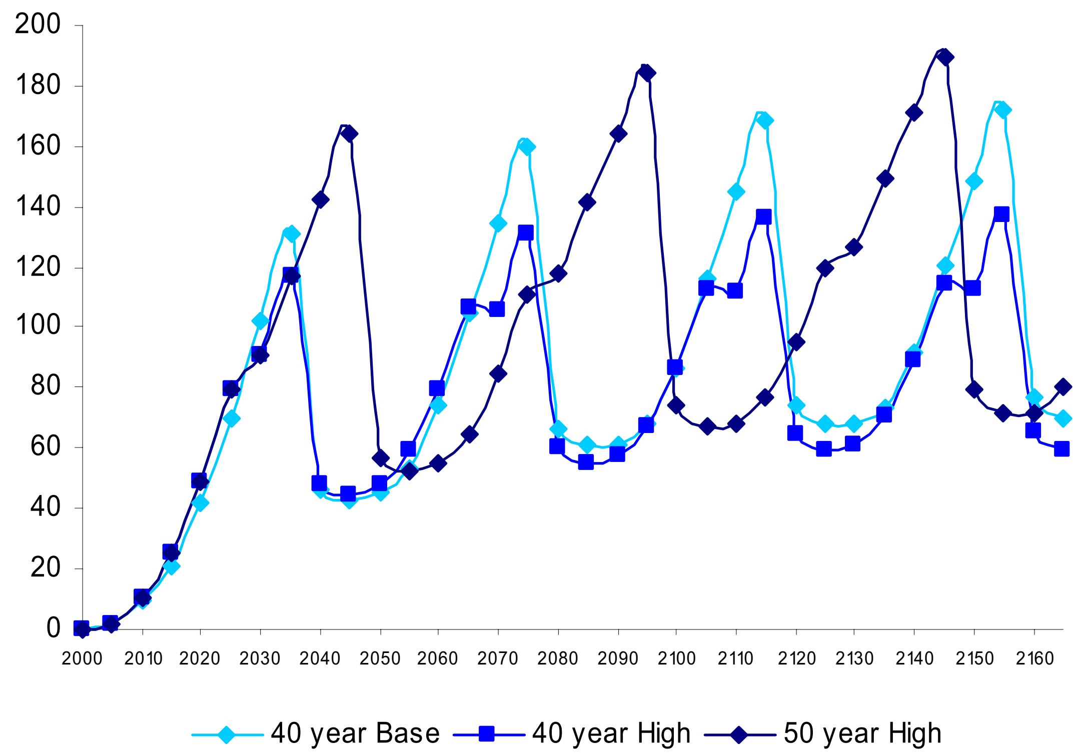

Figure 24. Net forest carbon for all management intensities through time in metric tons/ha.

All intensities sequester greater amounts of carbon from one rotation to the next, indicating a build up in the dead root and litter components, that remain higher than 50 metric tons/ha after the first rotation and through the 165 years considered. The litter component is part of the net gain from afforestation, maintained through reforestation in time. Another observation is that the difference in forest carbon between the 40 high and base management intensities gets bigger with time, from about 10 metric tons/ha in 2040 to about 40 metric tons/ha in 2160.

The 50 year high intensity management scenario reaches higher levels of forest carbon throughout the 165 years considered. The pattern of carbon accumulation seems to be reaching a steady state for both 40-year intensity management scenarios after the 4th rotation. The 40 base case scenario retains higher levels of carbon from one rotation to the next (more and bigger dead roots and litter), which manifests itself into higher levels of carbon sequestration overall through the management period considered. This level of carbon retained form one rotation to the next catches up with the 50 year rotation high intensity management after about four 40 year base rotations. Averages for the three rotations at different intervals of time are analyzed next, in order to show which management prescription sequesters more forest carbon depending on the window of time considered. Periods encompass forty years and consider the last harvest at years 40, 80, 120 or 160 to occur just after the interval, not before.

Average carbon sequestered is presented for four intervals of time through the management time considered for all intensities in Figure 25. The intervals follow the Rotation Length intervals to be compatible for further comparison, although scales have been adjusted to make patterns and trends more obvious among the closely related scenarios.

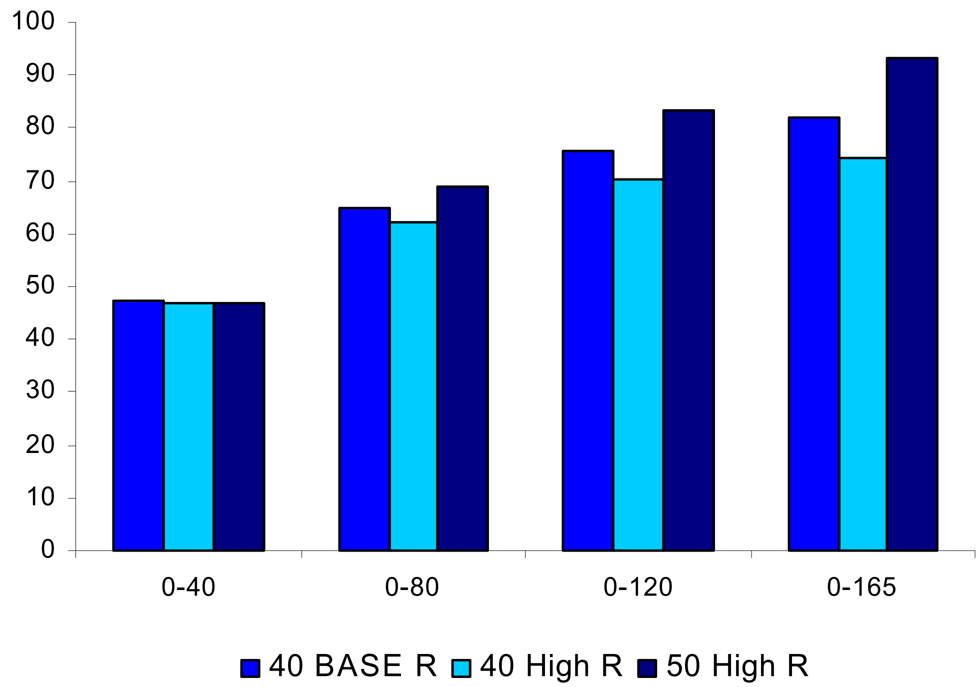

Figure 25. Average net forest carbon for all intensities in four intervals in MT/ha

The periodical average of net forest carbon sequestered increases for all management intensities and rotation lengths through time. The average goes from about 47 metric tons/ha for all rotations in the first interval to about 85 metric tons/ha for the 40 base case and 77 metric tons/ha for the 40 high intensity when considering the 165 years, with 60 and 45 % increase in their averages respectively. The base case sequestered about 10 % more carbon in the forest than the 40 year high intensity management, but this difference can only be appreciated after the second 40 year rotation.

As expected, the 50 year rotation sequesters more net average carbon than any of the two 40 year rotations at any interval of time considered. The 50 high intensity rotation goes from an average of about 65 metric tons/ ha (first interval) to almost a 100 metric tons/ha when considering the whole management period, a 53 % increase. The base case sequesters about 85 % on average of what the 50 year high intensity management scenario does.

In summary, the 50 high intensity rotation provides the greatest carbon sequestration at the forest level on average, followed by the base case and the 40 high intensity case.

4.2.3 The Carbon in Products

Carbon at the forest level is a very important pool, but there are other potential pools into which carbon can be stored for long periods of time. Part of this exercise is to incorporate and assess the transferring of the standing pools into the product pools and look at the trade offs (Table 20).

The first thing to notice is that total volumes harvested do not translate into total carbon sequestered in products. This is due to the commercial thinnings happening earlier in time than the final harvest, and those products derived from the intermediate operations having had time to decompose. Under such context, the base case sequesters a total of 102 metric tons/ha in products, barely higher than the total in products for the 40 high management intensity. However, the base case scenario has at the end of the rotation about 6 % less carbon in the long term product pool. The long term product pool is decayed at a 1 % per year, and it is constituted essentially of lumber for construction.

Table 20. Harvesting volumes and total carbon in products for the three rotations.

		40 mid INT	40 high INT	50 high INT
volume (ft3)	Pre commercial thin	412.55	516.06	516.06
	Commercial thin	0.00	924.71	924.71
	Regeneration harvest	4913.84	4319.86	5996.03
	Total Volume	5326.39	5760.63	7436.80
carbon (metric tons/ha)	long lasting products	49.77	53.02	67.96
	short lasting products	52.01	48.21	63.95
	Total Carbon	101.78	101.23	131.91

When addressing the longer rotation scenario, ten more years of growth are equivalent to 30 metric tons/ha more carbon in products, with almost 15 metric tons/ha more in long term products. This is to say that 10 more years of growth are equivalent to about 30 % more on the total average respect to both 40 year rotations, and about 36 % more than the base in the carbon average for the lumber pool.

4.2.3.1 Carbon Emissions from Forest operations and Manufacturing

Forest operations and manufacturing emissions, as explained previously, accumulate through time and must be subtracted from the total carbon sequestered in the different pools if any evaluation of potential carbon sequestration is to be balanced in time and space.

The differences in forest operation emissions are negligible among scenarios. The fertilizer application is included in the total emissions from forest operations, and it is added at the time of the commercial thinning (age 30) and ten years previously (age 20). There are barely any differences either, when looking at averages through time, among rotations in terms of manufacturing emissions (Figure 26).

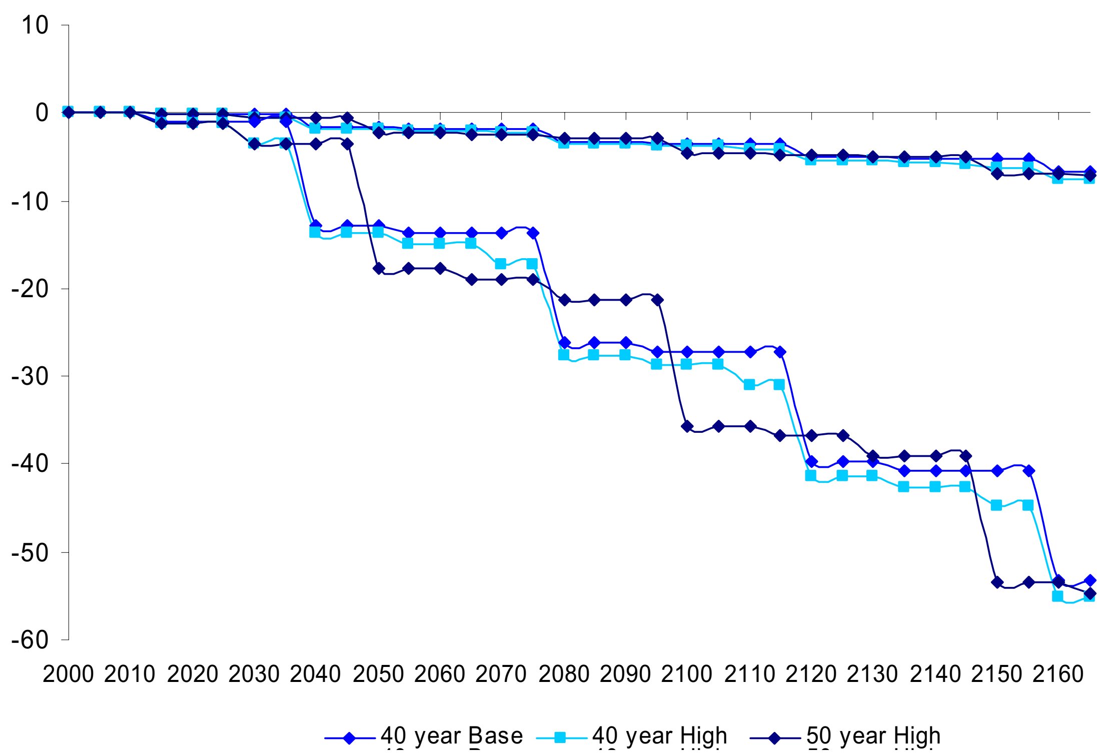

Figure 26. Forest operations and manufacturing emissions in metric tons/ha of carbon for all intensities and rotations through time.

4.2.3.2 Average Net Carbon in Products

Figure 27 shows net total products through the 165 years of management. The emissions from harvesting and manufacturing operations have been deducted.

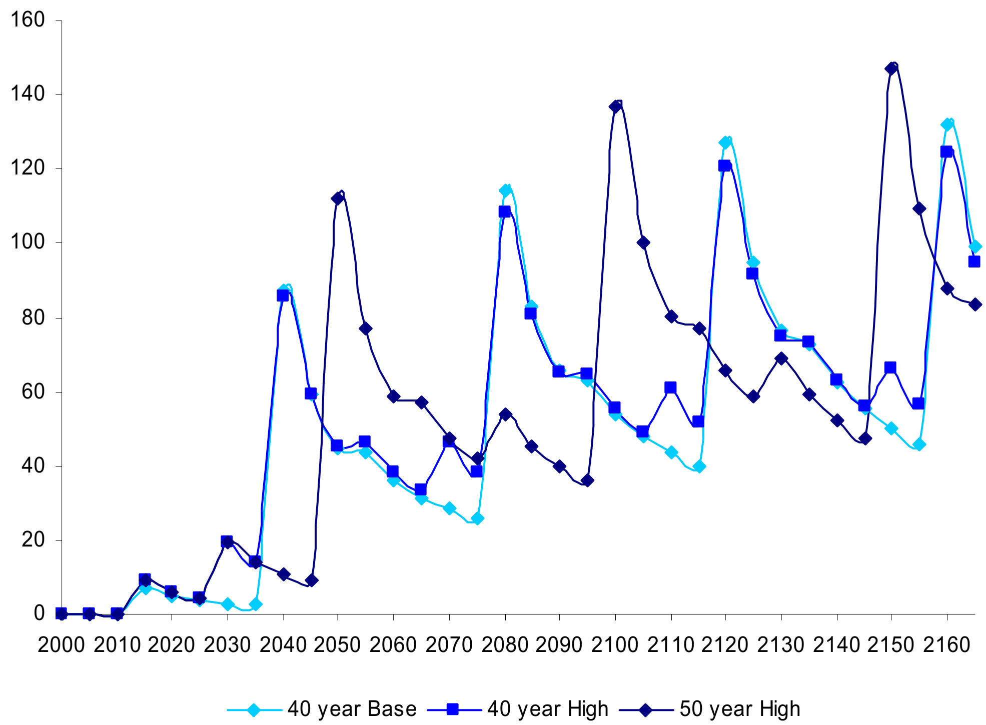

Figure 27. Net products in metric tons/ ha of carbon for all management intensities through time.

Carbon product pools are higher at time of harvest for the base 40 year rotation, but the 40 high intensity makes up for that difference with the commercial thinning. The total carbon amount in products increases through time for all intensities. Further inquiry into average periodical carbon sequestration is required to establish if ten more years of growth on three rotations make up for four shorter rotations in the 165 years described. Average carbon sequestered in products in different intervals is summed up in the following graph, with net carbon sequestered in the first 40 years, first 80 years, 120 and total for the management scenario (Figure 28). Forty years are considered per interval period assessed and consider the last harvest at years 40, 80, 120 or 160 to have occurred just after the interval, not before.

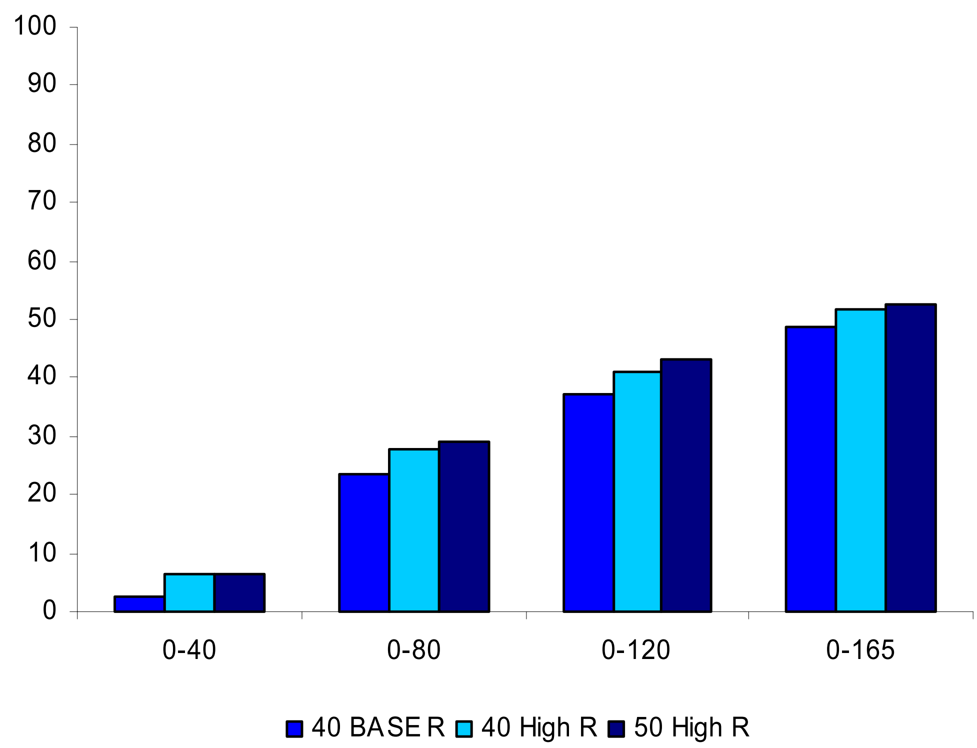

Figure 28. Average periodical carbon sequestered in product pools in four different intervals of time, in metric tons/ ha of carbon.

Average periodical sequestration of carbon in product pools increases through time for all intensities considered. The 40 base case scenario has the smallest amount of carbon in the products pool through time, at any interval considered. All intensities and rotations reach levels of above 50 metric tons/ha sequestered on average on a 165 year basis. The big difference observed in the first interval of 40 years is due to the lack of commercial thinning in the Base case scenario.

The 50 year scenario shown below sequesters the highest amount of carbon on average in its product pools (Figure 29).

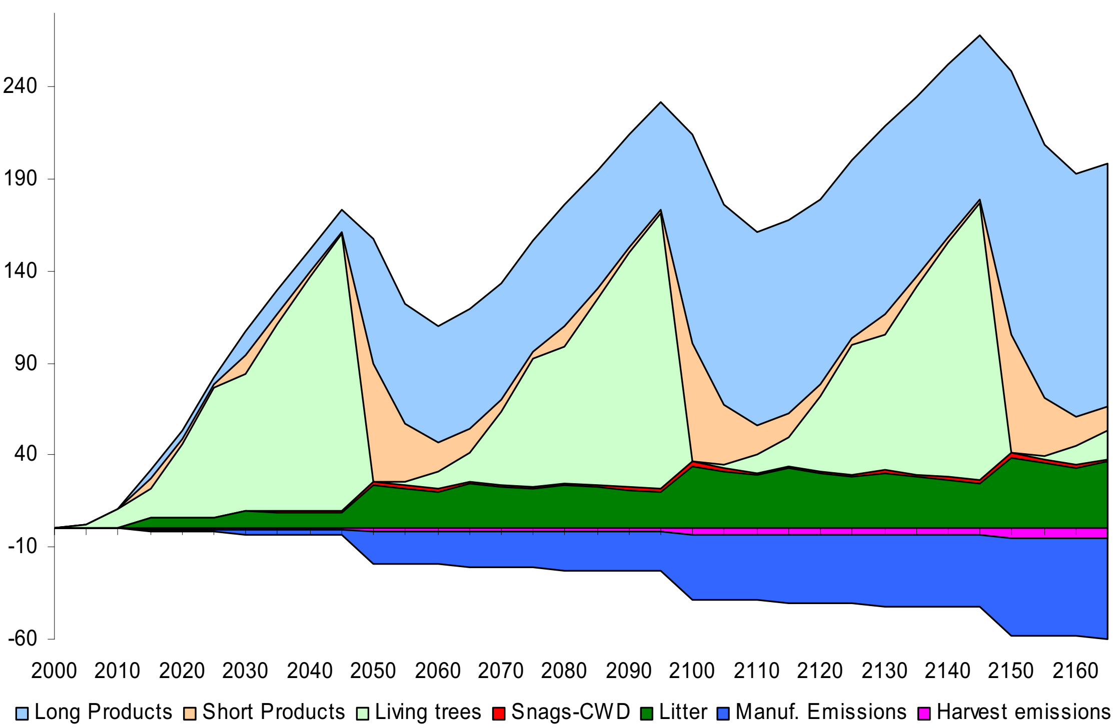

Figure 29. Carbon sequestration in the different pools by category, in metric tons/ha for the 50 high intensity rotation through time.

On average, the amount of carbon in products from three 50 year rotations under high intensity management (52.5 Mt /ha) is roughly equal to the carbon in products of four 40 year high intensity management rotations (51.8 Mt/ ha), with the higher intensity cases sequestering 8 and 6 % more carbon on average through the 165 years than the base case scenario.

As stated previously, the product pool is an important pool for carbon sequestration, and if put to a long term use, carbon can definitely accrue in time on an average basis. The short term products, because of a faster decomposition rate, are almost all gone by the end of the rotations (Figure 29). The long term products accumulate through time, corresponding to the pattern already observed in Figure 27. In Figure 29, forest operations and manufacturing emissions can be observed increasing through time, starting from an afforestation case, for the 50 year high intensity management rotation.

4.2.4. The Carbon in Forest and Products

The next step is to assess trade offs between intensity scenarios for the forest and product pools of carbon together through time, shown in Figure 30 as area under the curves. By the end of the 165 years of management, the 50 year rotation high intensity has sequestered an average of 149 metric tons/ha. This carbon average for the 50 rotation is 11 % higher than the average sequestered by the Base 40 year rotation, with 133 metric tons/ha in the combined pools. The 40 high intensity sequesters the least amount of carbon in the combined pools, at about 3 % less than the base case. The differential at the products carbon level is not enough for the 40 high intensity rotation to make up for the less carbon sequestered at the forest level.

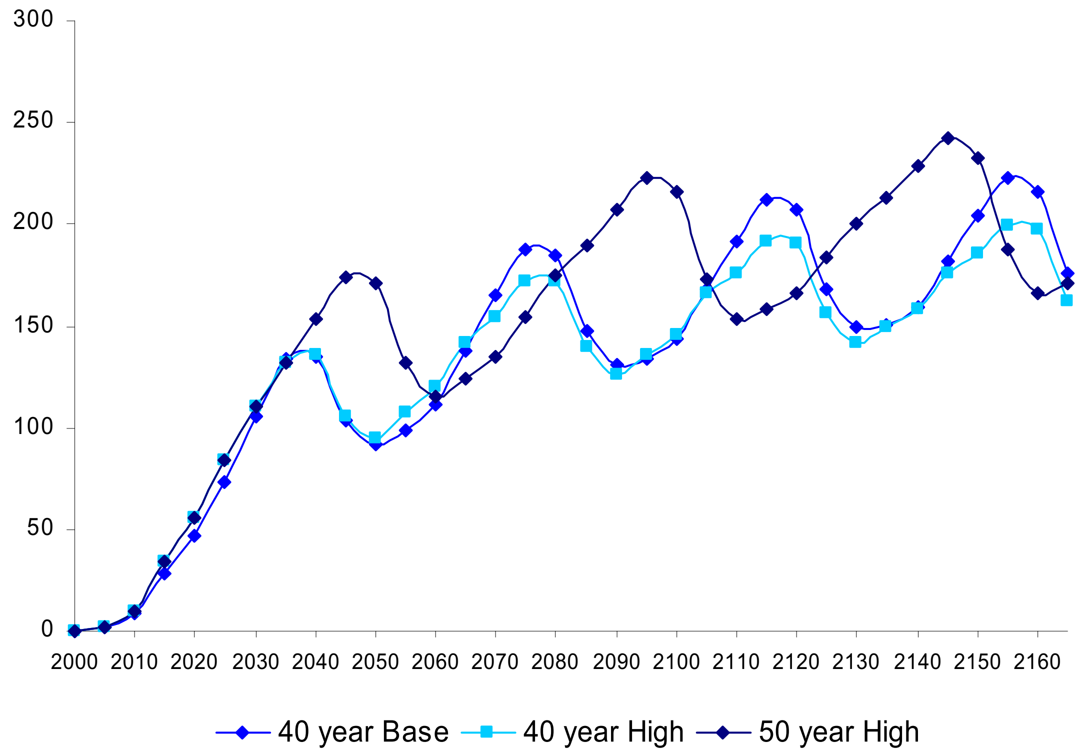

Figure 30. Net forest and net product carbon in metric tons/ha for all intensity scenarios through time.

All management intensities and rotations increase their carbon pools through time, a logical result of forest and products pools increasing on their own basis. The base case average total pool is always smaller than the 50 year high intensity management, and this average difference increases with time. The base case total average is smaller than the 40 high intensity for the first two intervals, and becomes greater when encompassing more than 120 years as the period of analysis (Figure 31). This change in patterns is mostly attributed to carbon residuals accumulating at the forest floor level after harvest operations.

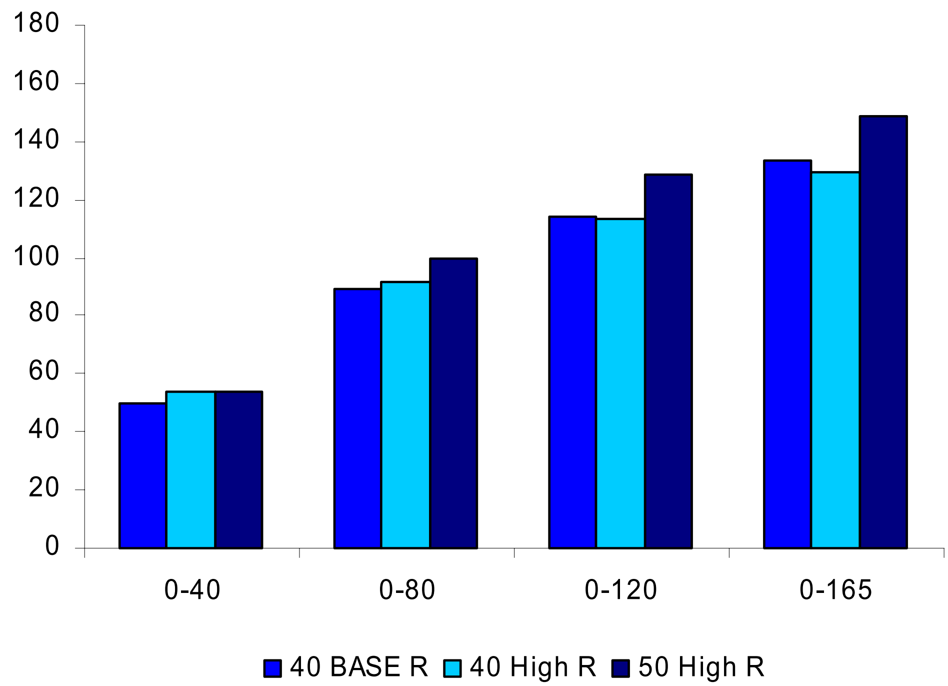

Figure 31. Net average in forest and product pools for all intensities in metric tons/ha at different intervals of time through the 165 years of management.

Table 21 presents a summary of the carbon pools and their estimates for the different management intensities and rotation lengths evaluated so far. The base case shows the least amount of carbon sequestered in forest products for all interval periods considered, followed by the 40 high and the 50 high rotations which is the greatest both in terms of forest and products carbon. The base case has greater amounts of carbon sequestered at the forest level which gives it higher overall pools later in time (after 120 years) against the 40 high intensity which sees the benefits of the higher amount of carbon in products in the first two intervals assessed. In first interval, the 40 high intensity is 7 % greater in forest and products carbon than the base case. This difference is reduced to 3 % when looking at 80 years as the interval.

Table 21. Summary table of averages for the forest, the products and the combined pools at different period intervals for all scenarios in metric tons/ ha.

	averages			
	0-40	0-80	0-120	0-165
40 year BASE				
NET FOREST	47.19	65.82	77.25	84.71
NET PRODUCTS	2.58	23.56	37.02	48.66
NET FOREST & PRODUCTS	49.77	89.38	114.28	133.37
40 high INT				
NET FOREST	46.97	63.35	72.13	77.53
NET PRODUCTS	6.60	27.89	40.92	51.78
NET FOREST & PRODUCTS	53.57	91.25	113.05	129.31
50 high INT				
NET FOREST	46.97	70.13	85.33	96.15
NET PRODUCTS	6.60	29.14	43.15	52.48
NET FOREST & PRODUCTS	53.57	99.27	128.48	148.62

The pattern is reversed in the third and fourth intervals, with the base case providing greater amounts of carbon than the 40 high intensity. The 50 year high intensity scenario is greater when compared to the base case on all intervals considered, with the difference slightly increasing with the interval of time considered, going from about 7 % more than the base in the first interval to about 12 % more carbon than the base in forest and products when looking at the 165 years considered.

4.2.5 Carbon displacement

Carbon displacement corresponds to the amount of carbon not emitted from the burning of fossil fuels when biomass is utilized instead while producing the same amount of energy. It is displacement and it is permanent and cumulative through time because fossil fuel emissions are replaced by non-fossil ones.

The analysis is based on the assumption that all short term products are used as biofuel in the wood boiler, replacing in such manner the burning of natural gas, with its correspondent carbon emissions from manufacturing burdened for the use of the co-products. The carbon manufacturing emissions representing the lumber production have only about a 50 % burden and therefore need to be adjusted to 100 % burden when using the short term products as biofuel. Forest operation carbon emissions stay the same.

The efficiency of a wood boiler is only 67 % compared to an 80 % for the fossil fuel boiler. This lower efficiency, together with the fact that the short term products are at a 50 % moisture (wet basis) make the amount of carbon not emitted, meaning displaced from fossil fuels, about half the carbon sequestered in short term products right after the regeneration harvest, on a metric tons/ha basis. However, as stated previously, the displacement is permanent and cumulative through time while short term products decompose rapidly according to our assumptions (1 %/ year on average). This property can be observed in Figures 32 for the 40 high intensity management scenario through the 165 years of management considered in the analysis. The long term products (light blue area) are shown stacked together with the displacement carbon (purple area) and the carbon in the short term products is shown as the black line.

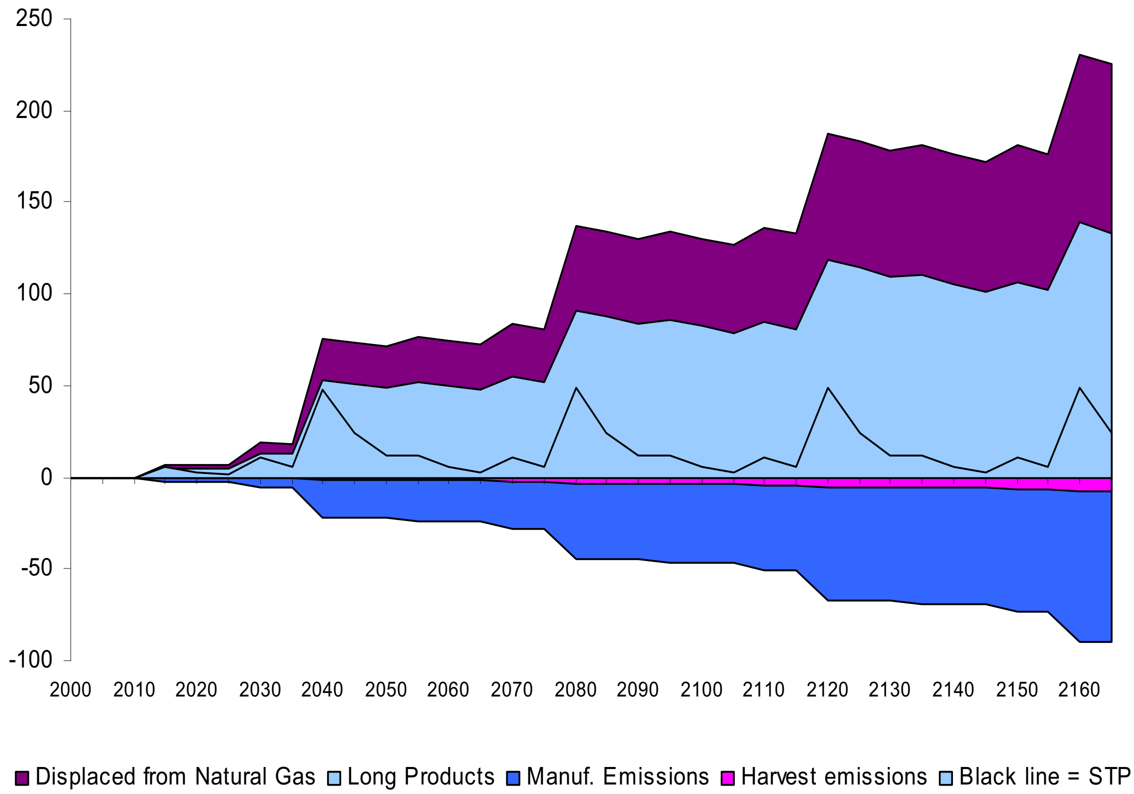

Figure 32. Carbon displacement against short and long terms products through time in metric tons of carbon /ha for the 40 high intensity management scenario.

The short term products and the displacement carbon do not exist at the same time, because the energy for the displacement comes from the burning of the totality of the short term products pool. Figure 32 is simply illustrating how the short term products pool, although greater than displacement on a 1:1 ratio, is almost totally gone through decomposition by the end of the rotation, while the carbon displaced keeps accumulating in time, becoming a net benefit in the overall carbon sequestration story by the time of the second rotation in this particular case.

Figure 33 shows the carbon displacement for all the management intensities through the scenario of 165 years considered.

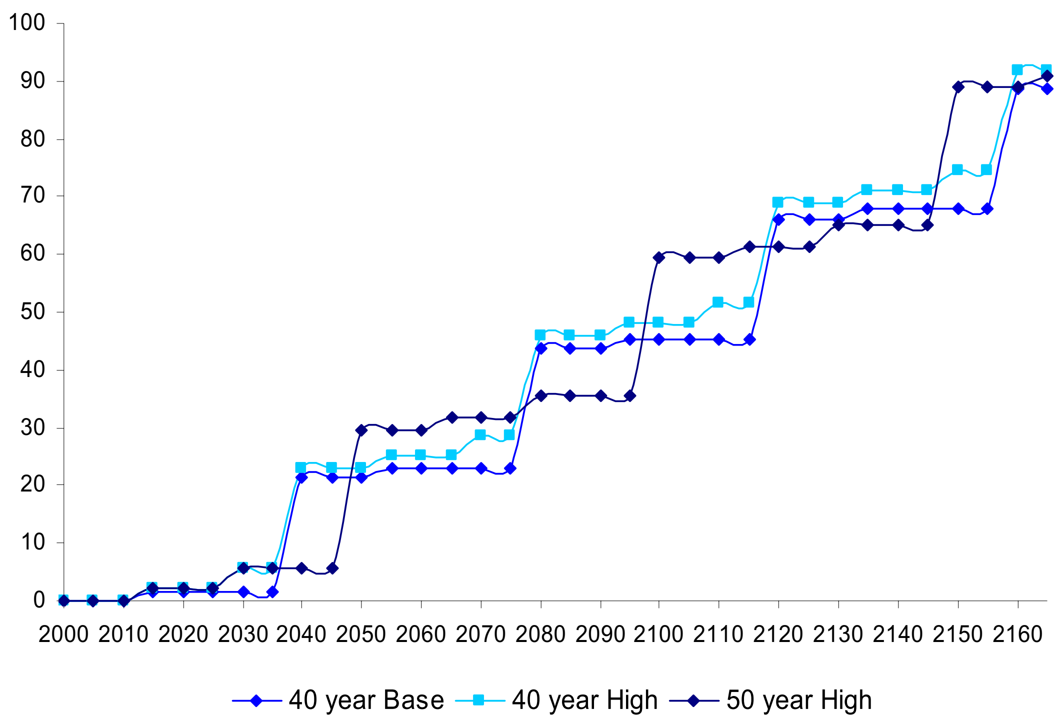

Figure 33. Carbon displaced from natural gas by burning biomass for all intensity rotations in metric tons/ha through time.

The base 40 rotation displaces 35.5 metric tons/ ha on average through the 165 years considered. The 50 high intensity rotation displaces an average of 37.68 metric tons/ha or 6 % more carbon than the base, followed by the 40 high intensity rotation with 8 % more carbon than the base displaced on average e, with 38.32 metric tons/ ha.

The displacement carbon does not change the overall pattern of the carbon sequestration differences among intensities and rotations. Table 22 shows the carbon average estimates when adding the displacement carbon to the already considered carbon averages in the forest and product pools in metric tons/ha.

Table 22. Summary of averages for the forest, the products and the combined pools with displacement at different period intervals for all scenarios in metric tons/ ha.

	averages 0-40	0-80	0-120	0-165
40 year rotation BASE				
NET FOREST	47.19	65.82	77.25	84.71
NET PRODUCTS	2.58	23.56	37.02	48.66
NET FOREST & PRODUCTS	49.77	89.38	114.28	133.37
NET FOR, PR & DISPLACMT	49.44	90.05	120.28	145.82
40 high INT				
NET FOREST	46.97	63.35	72.13	77.53
NET PRODUCTS	6.60	27.89	40.92	51.78
NET FOREST & PRODUCTS	53.57	91.25	113.05	129.31
NET FOR, PR & DISPLACMT	51.97	91.74	119.62	143.04
50 high INT				
NET FOREST	46.97	70.13	85.33	96.15
NET PRODUCTS	6.60	29.14	43.15	52.48
NET FOREST & PRODUCTS	53.57	99.27	128.48	148.62
NET FOR, PR & DISPLACMT	51.97	98.38	132.95	161.40

Displacement is a positive contribution to the carbon sequestration story in the long run, with higher levels of carbon sequestered on average for all intensities and rotations considered in the Intensity Management Case.

When considering the forty year interval, on average the amount of carbon sequestered is greater when using the short term products for something other than energy. When considering the 80 year interval, the total carbon pool is on average about the same with the displacement for all intensities and rotations than without the displacement, following the patterns described previously. However, when the interval is 120 years or more, the displacement has accumulated through time, proving to be a positive contribution to the carbon sequestration story in the long run.

The base case is still sequestering more carbon on average than the 40 high intensity management scenario when considering the 165 years of management, with the difference between the two slightly smaller than when no displacement was considered (2 % instead of 3 %). The 50 high intensity scenario is on average about 10 % greater than the base case.

Figure 34 shows the development of the carbon pools for the 50 year high intensity management scenario that has shown so far the greatest average levels of carbon sequestration.

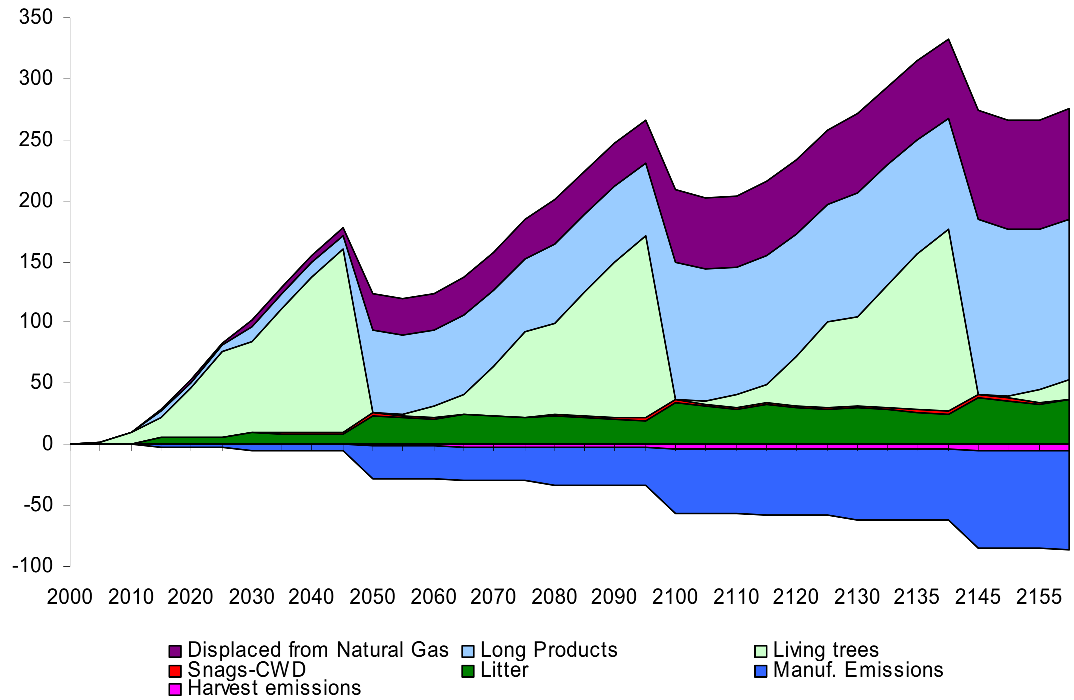

Figure 34. Carbon sequestered in the different pools through time for the 50 high intensity management in metric tons/ha.

4.2.6 Carbon substitution

As explained previously in the Methods, when no wood is harvested on the hectare, there are less wood framed houses / ha and more steel framed houses built / ha. This construction trade-off represents the basis for the substitution numbers. If wood is harvested at any point in time, wood will be substituting for steel and more wood framed houses will be built on the hectare, representing fewer emissions.

The number of potential wood houses from the regeneration harvest volumes ranges from 3 for the 40 high intensity management scenario, meaning minus 2 steel houses built per hectare, to up to 5 wood houses for the 50 high intensity management, equivalent to minus 4 steel houses built on the hectare, with the differential in carbon emissions associated to this different type of construction (Table 23).

Table 23. Changes in the number of wood and steel houses for different intensity rotations.

	2000	2015	2030	2040	2050
40 mi 3					
wood houses	-1.17	**-0.70**	-1.17	**4.39**	-1.17
steel houses	2.17	**1.70**	2.17	**-3.39**	2.17
40 mi 5					
wood houses	-1.17	**-0.58**	**-0.12**	**3.71**	-1.17
steel houses	2.17	**1.58**	**1.12**	**-2.71**	2.17
50 mi 5					
wood houses	-1.17	**-0.58**	**-0.12**	-1.17	**5.61**
steel houses	2.17	**1.58**	**1.12**	2.17	**-4.61**

The substitution factor dramatically changes the carbon sequestration story. Relative to the Base 40 rotation net forest and products carbon by including substitution at the house level, the 40 high intensity rotation always shows more sequestration than the base 40 rotation, even though before substitution came into play, the situation was the opposite (Figure 35).

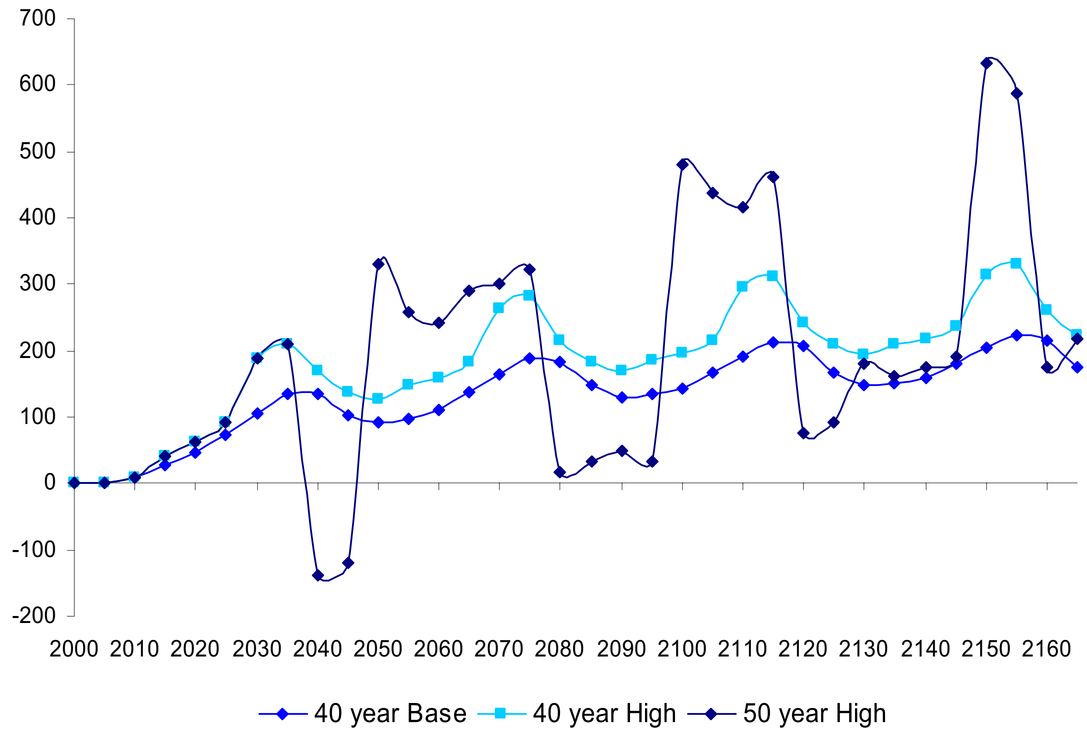

Figure 35. The 40 mid intensity rotation as base line (medium blue) for the substitution analysis against the other two cases, in metric tons/ha of carbon sequestered through the 165 years considered.

Because the rotation lengths are the same, and the only thing that changes is the intensity in the silvicultural management, it is readily observable that slightly higher volumes in harvesting and thinning are equivalent to great reductions in the amounts of carbon emissions when considering substitution of high fossil manufacturing materials. In the case of the 50 high intensity rotation, although starting positive, it goes negative in 2040 when the base and shorter rotations are harvested, and slowly recovers to positive levels again after 2050, when the first regeneration harvest occurs for that management scenario.

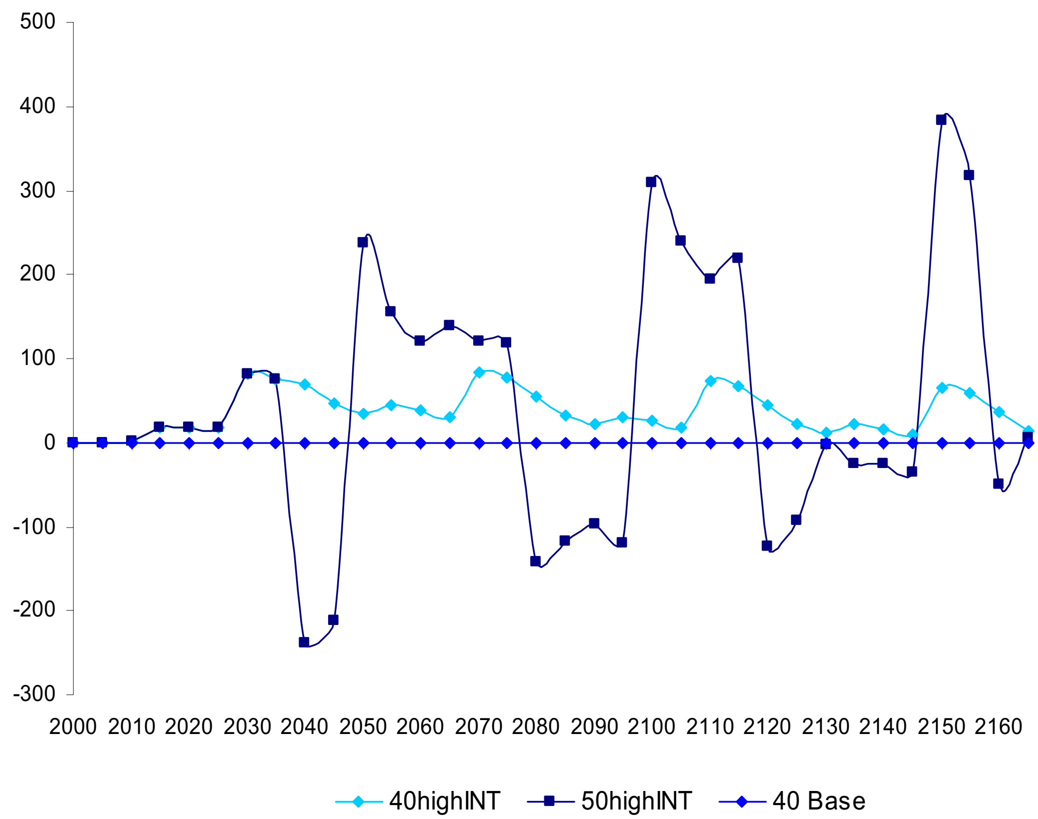

Figure 36. Same picture as Figure 35, but with the Base 40 normalized to zero.

When the base line is normalized to zero (Figure 36), the carbon differential among the base and the 40 high intensity management can be observed to diminish through time, even though the 40 high intensity management is still considerably above the base throughout the 165 years considered. The longer rotation ? but shows a positive trend overtime.

Figure 37 shows average carbon against the base rotation for the four intervals of time previously considered when addressing effects of substitution within the carbon sequestration story. The base case is now the smallest on average carbon sequestration at any interval of time, while before addressing substitution it was only smaller in the short run. When considering the 165 years of management, the 40 and 50 high intensity management scenarios sequester about 38 % and 43 % more carbon respectively than the base. Less fossil fuels were used by the wood substitution provided by these scenarios.

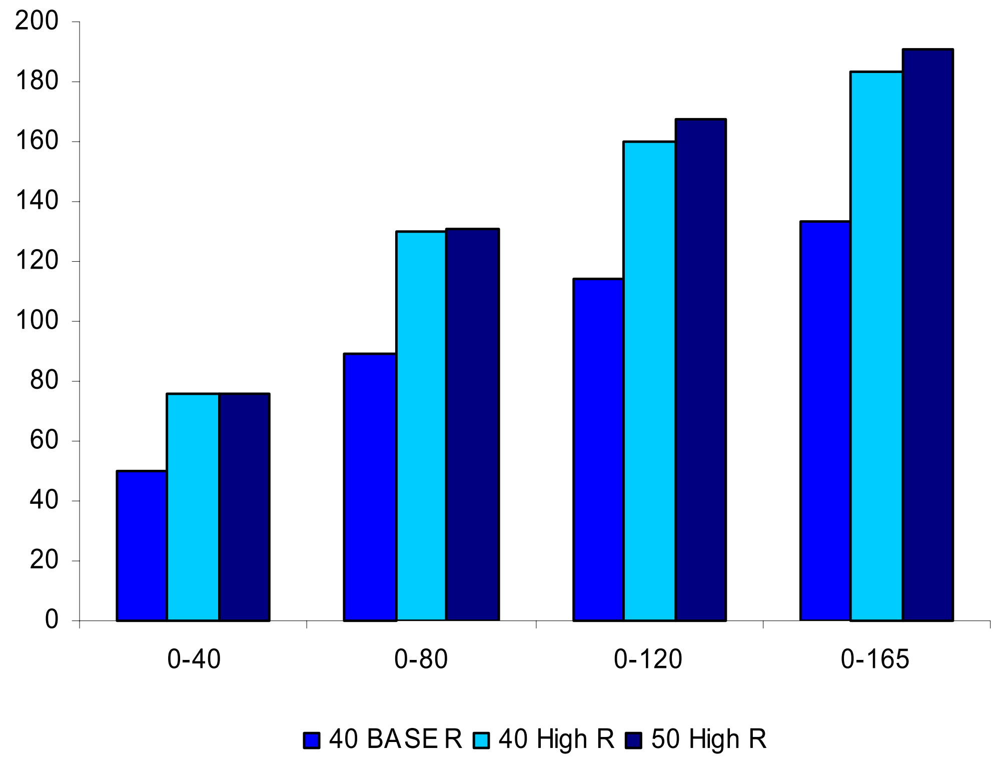

Figure 37. Average carbon sequestration differentials against the base 40 with average forest and products carbon, when incorporating substitution in metric tons/ha for the defined interval of time.

The 40 and 50 high intensity management scenarios are very close in terms of their carbon sequestration potential when addressing all the components considered in the carbon story in the first two intervals with no additionality from the 10 extra years of growth in the short time. However, the last two intervals show an additionality from the 50 high intensive rotation of about 7 metric tons/ha on average

Table 24 shows the summary of the carbon story, at the forest, products, displacement and substitution levels.

Table 24. Summary table of averages for the forest, the products and the combined pool with displacement and substitution at different period intervals for all scenarios in metric tons/ ha.

	averages			
	0-40	0-80	0-120	0-165
40 year rotation BASE				
NET FOREST	47.19	65.82	77.25	84.71
NET PRODUCTS	2.58	23.56	37.02	48.66
NET FOREST & PRODUCTS	49.77	89.38	114.28	133.37
NET FOR, PR & DISPLACMT	49.44	90.05	120.28	145.82
NET STDG, PR, SUBST..	49.77	89.38	114.28	133.37
40 high INT				
NET FOREST	46.97	63.35	72.13	77.53
NET PRODUCTS	6.60	27.89	40.92	51.78
NET FOREST & PRODUCTS	53.57	91.25	113.05	129.31
NET FOR, PR & DISPLACMT	51.97	91.74	119.62	143.04
NET STDG, PR, SUBST..	75.90	129.82	160.33	183.67
50 high INT				
NET FOREST	46.97	70.13	85.33	96.15
NET PRODUCTS	6.60	29.14	43.15	52.48
NET FOREST & PRODUCTS	53.57	99.27	128.48	148.62
NET FOR, PR & DISPLACMT	51.97	98.38	132.95	161.40
NET STDG, PR, SUBST..	75.90	130.94	167.76	190.85

So far, the carbon story has only been addressed at the standing or products level. If only looking at those two pools, the 40 high intensity makes more sense in terms of the carbon pool sequestered and the economics of the investment. It is followed by the 50 high intensity, where 10 more years of growth are shown to provide significant increases in the carbon pools at a modest economic cost. The carbon story does not change this pattern when incorporating the displacement carbon. When considering the substitution effects, slightly higher levels of carbon sequestration are provided with the 50 high intensity rotation than the 40 high intensity rotation, with slightly poorer economic returns.

5. DISCUSSION

The discussion section will be addressed in two parts. First, the carbon model and its assumptions will be assessed with regards to the quality and reliability of the outputs and potential places for improvement. Secondly, the results from the Rotation and Intensity case scenarios will be explored looking for the greatest potential for sequestration and reduction of emissions, while addressing the economic trade offs of the different alternatives of management explored.

5.1 The Carbon Model

The significance of the carbon model created for the Pacific Northwest region lies in that all of the components considered important in the carbon sequestration story are incorporated in it, and all are based on outputs from a specific forest stand. In this way, forest carbon, products carbon, displacement and substitution carbon issues as well as the economic tradeoffs can be evaluated by the landowner and incorporated in the management strategy whether based on objectives that are local (jobs, regulations, economics) and/or global (land use changes, environment, global warming).

5.1.1 The Forest Module

The Forest Module is a first step in developing a close carbon model for the Pacific Northwest region. Even though it is considered a closed model, there are components that need to be addressed in the future and their contribution to the carbon cycle reassessed.

For example, we are not addressing the understory component, and justifying it because of the small amount of biomass relative to the overall stand and difficulties in the modeling of its development. In their study on a series of Douglas-fir stands, Turner and Long (1975) found that even though the understory is less than 5 % of the total standing biomass, it was a significant portion of the total stand productivity (up to 17 %) and even a higher proportion of the organic matter returned to the forest floor (up to 43 % of the total return). Changes in site productivity are not addressed in the model but it is understood that site productivity is not a fixed nor given attribute and the understory component might be a critical element of that productivity in its interaction and contributions to the carbon soil.

The model assumes that the entire crown is left on site after harvest, and none of the material is burned as site preparation for the regeneration planting. Leaving the slash on the ground is beneficial for nutrient cycling and avoidance of immediate emissions. These assumptions might have to be revised to be closer to the reality of the management in the Pacific Northwest forest. Although those practices would be ideal for the maintenance of the forest floor component, they can be counter productive in the regeneration process.

The estimated dry weight biomass outputs from Gholtz et al (1979) regression equations have been tested and used previously in several biomass studies. Therefore it is not surprising to find all of the outputs within ranges estimated for the region, according to site productivity, age and density of the stand in question (Grier & Logan 1977, Keyes 1979, Edmonds 1980, Vogt et. al. 1980, Gholtz 1982, Cooper 1983, Keyes & Grier 1981, Santantonio & Herman 1985, Vogt et. al. 1986, Edmonds 1987, Vogt 1991).

The way decomposition is calculated for the different components in the carbon model is not related to moisture nor temperature changes within the stand, even though the literature suggests they are directly correlated. Harvesting usually increases decomposition rates of the forest floor material because it causes higher soil temperatures and moisture (Aber et al 1978). Temperature and moisture variables have been found to be the main factors explaining decomposition patterns (Gholtz et al 2000). These variables can change considerably in the development of a stand, especially after harvesting or thinning operations. The model does not account for these changes at the stand scale and the simple way in which the model is estimating decomposition carbon losses to the atmosphere could be refined.

There is also the issue of scale. There is carbon loss from an individual tree as it decomposes (i.e. snags) however, if looked at as a group of snags, they still result in accumulation of carbon storage over time, even though the individuals are decomposing (Harmon 2001). There is not a single scale that is correct for the evaluation of carbon, but caution needs to be exerted when looking at the addition of outputs at the stand level, because some of these might not be directly transferable to a higher scale of assessment, such as in the detritus component.

Although forest inventory data may provide the best available information on carbon accumulation at the forest stand level, it is not enough to calculate total forest ecosystem carbon. An ecosystem-level carbon model should integrate changes in detritus and soil carbon together with the tree carbon changes, as well as land use change data to be able to better assess, understand and predict net carbon storage in managed and disturbed forest ecosystems.

5.1.2 The Products Module

The products module is largely based on the CORRIM (2002) interim report "Life Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Building Construction Substitution". Some of the assumptions within specific appendixes in the Report are still being refined. Until the Report is peer reviewed, some of the inputs and outputs used in the products module might continue to change.

For example, the long term storage products within the product module of the carbon model does not consider plywood even though it represents more than 25 % of the total production in the five manufacturing plants surveyed in the Pacific Northwest.

In the lumber assessment, there is potential for error in the material balance when going from conversion of wood volume (ft^3) given by LMS volume output tables to the log scale volume (Scribner) required for the use of the outputs given by the mills. This conversion is dependent on log sizes, and as of now, the products stream of outputs is solely based on volume, without addressing the diameter of the logs and the sensitivity of this conversion. The value of larger logs that yield higher lumber grades and have higher monetary and plausible mechanical values are ignored in the model. Diameter is used to determine the volume of sawlogs available.

Issues with regards to the manufacturing emissions can be customized for specific mills. The initial case assumed essentially no use of residuals for energy production.

5.2. The Case Scenarios

5.2.1 The Rotation Case

When considering carbon sequestration alternatives and the possible questions to explore, the idea that longer rotations might be more beneficial in the accounting of carbon than shorter rotations was inevitable. Most of the literature seems to convey this point of view, by addressing the carbon at the forest level in longer rotations versus shorter rotations, which is readily obvious because of the greater biomass produced, or indirectly, by arguing issues of old growth conversion to younger stands (Cooper 1983, Harmon et al 1990, Dewar 1991, Schultze et al 2000).

The study results show this to be true for carbon at the forest level, but not when product flows including substitute products are included. The carbon patterns observed at the forest level are reversed when looking at substitution issues. The carbon sequestration losses from substituting other materials for wood more than offsets the increase carbon storage in the forest at least for the first several hundred years, a period exceeding normal carbon targeting. These issues have been mostly ignored by the literature (Harmon et al 1990, IPCC 2000). The IPCC report on land use addresses long term sink capacity. It states that "additional carbon can be stored in an ecosystem only if more carbon is kept for the same period of time or the same amounts of carbon are kept over longer periods of time", with harvesting negatively impacting these increased sinks. Again, the IPCC statement is true when addressing forest level sink issues. The statement does not provide an overall vision for the role of wood in the substitution scheme within the carbon cycle and all of its components.

From a policy perspective, providing carbon credits for longer rotations will not make much sense and might even be counterproductive unless the targets of interest are hundreds of years in the future. Credits for longer rotations, because of the tradeoffs in the substitution of wood by more fossil and energy intensive manufactured products, can become detrimental when considering the full analysis. However, using a carbon tax that differentially affects fossil fuel consumption would be a potential way to deter individuals, communities and industries from using fossil fuel intense wood substitutes, and thus reduce the amount of carbon emissions.

The Rotation case analysis showed that the hypothesis that long rotations are good both for biodiversity and carbon is not true when looking at the full carbon assessment. The Rotation case also showed the significant contribution of afforestation in the carbon accounting, which has been often suggested by the literature (UNFCC 1998, Chomitz 2000, Birdsay et al 2000). Moreover, harvesting afforested lands will sequester even more carbon through product pools than not harvesting. Even though no management can sequester more carbon at the forest level, it is counterproductive by not producing renewable wood products that will substitute for fossil fuel intensive products.

The benefits of the afforestation activities gave rise to the idea for a carbon credit on afforestation. If afforestation can be estimated and monitored through time, the idea of implementing a carbon credit on afforestation seems plausible benefiting the landowner while providing incentives to avoid land use change, which more usually than not result in deforestation.

Figure 38 shows the average carbon sequestered in forest and products pool on a 40 year case scenario. The average indicated by the red line in the figure is about 90 metric tons/ha over the 80 years considered. If $5 are paid per metric ton of carbon, the combination of this incentive plus the SEV return from forestry alone would double the landowner's return producing a high motivation to keep land in forestry or convert other land with a low return to forestry.

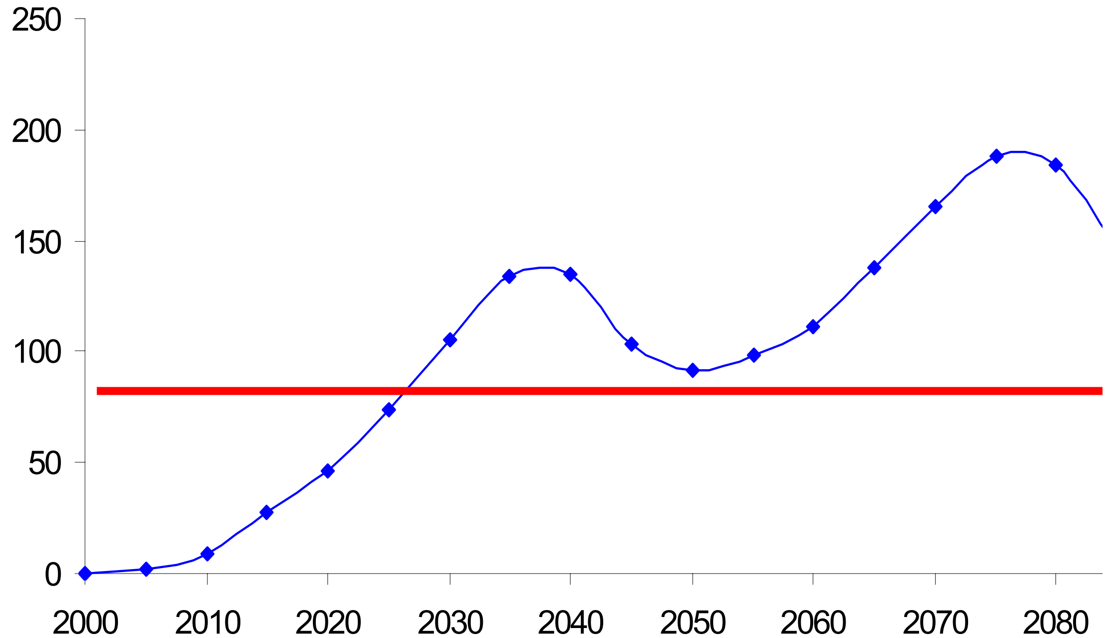

Figure 38. Carbon in forest and product pools for Base 40 year rotation in metric tons/ha through 80 years from afforestation through reforestation.

The biodiversity value of longer rotations cannot be ignored. When values and objectives other than carbon override the full carbon assessment scheme, such as habitat and biodiversity concerns, long rotations might be appropriate.

From this analysis it is clear that mitigation of carbon emissions depends on the extent to which fossil fuel use is displaced by biofuel and wood products. Hence the full assessment developed here is important.

5.2.2. The Intensity Case

The intensity case looked at differentials in carbon pools at the forest, products, displacement and substitution levels when managing a stand to different intensities. The idea was to be able to define where additionality might occur, if from higher levels of thinning and fertilization, or from slightly longer rotations.

One would expect that more intensive management would produce more sequestration in the products pools. The results show that while thinnings reduce the carbon in the forest, the gain in carbon product flows which can substitute for fossil intensive products, more than offset that loss at the forest level.

While it did not come as a surprise that modest increases in management intensity provided better economics, the differences were modest. Since many landowners continue to manage much like the base case, adding even small carbon credit incentives might allow for an increase in the management intensity thereby sequestering more carbon at a very low cost.

This can be observed in figure 39 where significant differences among intensity management regimes can be found in the amount of carbon sequestered. When considering the first 40 year interval (1), there are about 26 more metric tons/ha of carbon in the intensive 40 and 50 year rotations than in the base case. This differential increases to about 30 when looking at the 80 year interval (2). There is no differential at that point in time attributed to additionality between the 40 and 50 high intensity rotations.

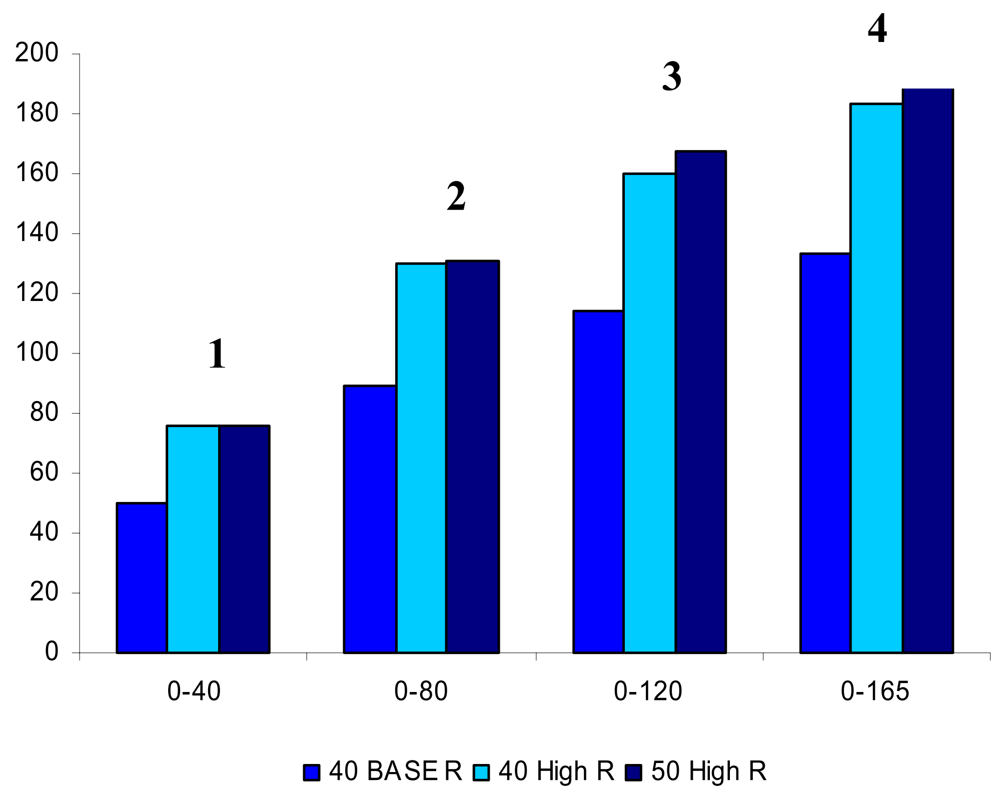

Figure 39. Carbon pools in forest, products when substitution is considered, for all intensities at different intervals of time through the management scenario.

Intervals 3 (0-120 years) and 4 (0- 165 years) show carbon additionality between the 40 high and 50 high intensity rotation. While extending the rotation slightly (i.e. 10 years) sequesters somewhat more carbon, the economic loss to the owner to produce about 7 more metric tons/ha of carbon would require a comparable carbon credit. This credit should be more or less equal to the differences in SEV divided by number of additional acres, in this case 83 / 7 = $12. The target is still deemed to be too far out in time to be of consideration.

5.3 Closing remarks

While the displacement of fossil fuels by burning short lived products for energy increases carbon sequestration since the displacement is permanent and does not decay like short lived products, the low efficiency in the conversion results in little short term benefit. After several rotations the increase sequestration can become significant. However, the length of time required would appear to be beyond useful carbon credit targets.

The model demonstrates the level of complexity needed to adequately account for carbon sequestration related to forest management. Carbon credit systems will have to be very complex not to induce unintended consequences (i.e. emissions from renewable vs. non renewable resources).

Increasing afforestation and intensifying forest management are possible objectives. While longer rotations have many environmental benefits, such as biodiversity and habitat for endangered species, they are more likely to produce substitution from fossil fuels than increased carbon storage in the short term.

A general increase in the cost of fossil fuels or a tax will encourage both afforestation and intensive management. As little as $ 5 / metric ton of carbon was shown to double the expected land value for the high intensive rotation case. This should be enough of an incentive to convert marginal agricultural lands to forest land.

5.4. Future work

A complete sensitivity analysis should be done to evaluate specific products and their end use. The decaying functions should be more complex to represent more accurately the decomposition of the forest components and the life of the forest products. When reliable impacts of management regimes on soil carbon become available they should be added to the model.

Given the interest in carbon credit incentives, it could be important to assess in what situations an incentive might contribute to afforestation without causing deforestation somewhere else. Perez- Garcia (1994) showed that market incentives produce at least partially offsetting?. Furthermore, it will be important to assess when and under what conditions substitution would not be the model in which to base the full analysis for carbon sequestration.

6. BIBLIOGRAPHY

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7. APPENDICES

7.1 APPENDIX A: FOREST

7.1.1 Biomass equations

Each component has species-specific equations and coefficients to accomplish the computations. The following defines the known species, equation used, and respective coefficients.

Equation 1: Biomass = $\exp^{(b0)} * (dbh^{b1})$
Equation 2: Biomass = $b0 + b1 * (d^2 * ht/100)$
Equation 3: Biomass = $b0 + b1 * (d^2 * ht/100) - b2 * (d^2 * ht/100)^2$

Species = Equation number, b0, b1, b2

Foliage Biomass

Big Leaf Maple (*Acer macrophyllum*) = 1, -3.7650, 1.6170, 0.0000
Grand Fir (*Abis grandis*) = 1, -2.8462, 1.7009, 0.0000
Red Alder (*Alnus rubra*) = 2, 0.5124, 0.1298, 0.0000
Western Hemlock (*Tsuga heterophylla*) = 1, -4.1300, 2.1280, 0.0000
Douglas fir (*Pseudotsuga menziesii*) = 1, -2.8462, 1.7009, 0.0000
Western red cedar (*Thuja plicata*) = 1, -2.8462, 1.7009, 0.0000

Litter fall Biomass

Big Leaf Maple (*Acer macrophyllum*) = 1, -2.1160, 1.0920, 0.0000
Grand Fir (*Abis grandis*) = 1, -3.5290, 1.7503, 0.0000
Red Alder (*Alnus rubra*) = 1, -2.1160, 1.0920, 0.0000
Western Hemlock (*Tsuga heterophylla*) = 1, -2.4090, 1.3120, 0.0000

Douglas fir (*Pseudotsuga menziesii*) = 1, -3.5290, 1.7503, 0.0000
Western red cedar (*Thuja plicata*) = 1, -3.5290, 1.7503, 0.0000

Root Biomass

Big Leaf Maple (*Acer macrophyllum*) = 1, -3.4930, 2.7230, 0.0000
Grand Fir (*Abis grandis*) = 1, -4.6961, 2.6929, 0.0000
Red Alder (*Alnus rubra*) = 3, 0.1000, 0.4800, 0.0005
Western Hemlock (*Tsuga heterophylla*) = 1, -4.6961, 2.6929, 0.0000
Douglas fir (*Pseudotsuga menziesii*) = 1, -4.6961, 2.6929, 0.0000
Western red cedar (*Thuja plicata*) = 1, -4.6961, 2.6929, 0.0000

Live Branch Biomass

Big Leaf Maple (*Acer macrophyllum*) = 1, -4.2360, 2.4300, 0.0000
Grand Fir (*Abis grandis*) = 1, -3.6941, 2.1382, 0.0000
Red Alder (*Alnus rubra*) = 1, -4.2360, 2.4300, 0.0000
Western Hemlock (*Tsuga heterophylla*) = 1, -5.1490, 2.7780, 0.0000
Douglas fir (*Pseudotsuga menziesii*) = 1, -3.6941, 2.1382, 0.0000
Western red cedar (*Thuja plicata*) = 1, -3.2661, 2.0877, 0.0000

Stem Biomass

Big Leaf Maple (*Acer macrophyllum*) = 1, -3.4930, 2.7230, 0.0000
Grand Fir (*Abis grandis*) = 1, -3.0396, 2.5951, 0.0000
Red Alder (*Alnus rubra*) = 3, 0.0200, 1.6000, 0.0005
Western Hemlock (*Tsuga heterophylla*) = 1, -2.1720, 2.2570, 0.0000
Douglas fir (*Pseudotsuga menziesii*) = 1, -3.0396, 2.5951, 0.0000
Western red cedar (*Thuja plicata*) = 1, -4.1934, 2.1101, 0.0000

Bark Biomass

Big Leaf Maple (*Acer macrophyllum*) = 1, -4.5740, 2.5740, 0.0000
Grand Fir (*Abis grandis*) = 1, -4.3103, 2.4300, 0.0000
Red Alder (*Alnus rubra*) = 1, -4.5740, 2.5740, 0.0000
Western Hemlock (*Tsuga heterophylla*) = 1, -4.3730, 2.2580, 0.0000
Douglas fir (*Pseudotsuga menziesii*) = 1, -4.3103, 2.4300, 0.0000
Western red cedar (*Thuja plicata*) = 1, -4.3103, 2.4300, 0.0000

From: Gholz, H.L., C.C. Grier, A.G. Campbell, and A.T.Brown. 1979*. Equations for estimating biomass and leaf area of plants in the Pacific Northwest*. Forest Research Lab, Oregon State University, Corvallis, Oregon.

7.1.2. Factors to convert tree biomass to carbon (kg)

Region	Forest Type	Softwood	Hardwood
Rocky Mountain and Pacific Coast	Douglas-fir	0.512	0.496
	Ponderosa Pine	0.512	0.496
	Fir-Spruce	0.512	0.496
	Hemlock-Sitka Spruce	0.512	0.496
	Lodgepole pine	0.512	0.496
	Larch	0.512	0.496
	Redwoods	0.512	0.496
	Hardwoods	0.512	0.496

From: Birdsay, R.A. 1992. Carbon storage and accumulation on United States forest ecosystems. USDA Forest Service General Technical Report. WO-59.

7.1.3 Constants for decomposition and mortality used in woody debris dynamics

Forest Type	Decomposition	Mortality
Douglas-fir	0.018	0.005
Ponderosa Pine	0.015	0.005
Fir-Spruce	0.024	0.005
Hemlock-Sitka Spruce	0.029	0.006
Lodgepole pine	0.036	0.0045
Redwoods	0.012	0.0021
Hardwoods	0.067	0.006

From: Harmon, M. 1993. Woody debris budgets for selected forest types in the U.S. Pages 151-178 in D.P Turner, J.J Lee, G.J Koerper, and J.R. Barker editors. *The forest sector carbon budget of the United States: carbon pools and flux ender alternative policy options.* EPA/600/3-93/093. United States Environmental Protection Agency, Corvallis, Oregon, USA

7.1.4 Snag densities

Decay Class	Douglas Fir	Western Hemlock
I	0.390	0. 383
II	0.369	0.319
III	0. 221	0.230
IV	0.166	0.172
V	0.127	0.127

(density in grams of dry mass per cubic centimeter of green volume)

From: Spies, T.A.,J.F. Franklin, and T.B. Thomas. 1988. *Coarse woody debris in Douglas-fir forests of western Oregon and Washington*. *Ecology* 69:1689-1702.

7.1.5 Wood densities for selected tree species

Coastal Douglas fir :	0.45
Interior Douglas fir:	0.46
Western hemlock :	0.42
Pacific silver fir:	0.40
Western red cedar:	0.32
Red alder:	0.37

From : Hartman, D.A., W. A. Atkinson, B.S. Bryant and R.O Woodfin. 1976. Conversion factors for the Pacific Northwest forest industry; Converting forest growth to forest products. Institute of Forest Products, Seattle, Washington.

7.2 App B : Products CORRIM

Summary mill data for wood component.

Exported results from SimaPro LCI for raw materials from the production of one Mbf of planed dry lumber

Exported results from SimaPro LCI for air emissions from the production of one Mbf of planed dry lumber

7.3 Appendix D : Economic analysis

Based on Kevin Zobrist model for the PNwest.

Codes:	1	2	3	4	5
	Plant	Veg	PCT	CT	CC

REVENUES AND COSTS ROTATION CASE

		2010	2025	2035	2055	2075	2085	2115	1995
120 year	*Revenue*	-$44	$1,211		$4,771		$7,747	$29,294	
	Log cost		$907		$1,539		$2,050	$6,333	
	Stumpage		$304		$3,233		$5,697	$22,961	
	Net	-$62	$304		$3,233		$5,697	$22,961	-$263
	Code	3	4		4		4	5	1
40 base	*Revenue*	-$56		$10,291					
	Log cost			$3,983					
	Stumpage			$6,309					
	Net	-$62		$6,309					-$263
	Code	3		5					1
80 year	*Revenue*	-$56	$1,198		$4,835	$20,761			
	Log cost		$907		$1,539	$4,726			
	Stumpage		$290		$3,296	$16,035			
	Net	-$62	$290		$3,296	$16,035			-$263
	Code	3	4		4	5			1

REVENUES AND COSTS INTENSITY CASE

		2010	2025	2035	2040	2045	1995
40 base	*Revenue*	-$56		$10,291			
	Log cost			$3,983			
	Stumpage			$6,309			
	Net	-$62		$6,309			-$263
	Code	3		5			1
40 high	*Revenue*	-$30	$1,398	$9,019			
	Log cost		$1,027	$3,186			
	Stumpage		$371	$5,833			
	Net	-$62	$371	$5,833			-$263
	Code	3	4	5			1
50 high	*Revenue*	-$30	$1,356			$12,963	
	Log cost		$1,027			$3,732	
	Stumpage		$329			$9,231	
	Net	-$62	$329			$9,231	-$263
	Code	3	4			5	1

CASH FLOW ROTATION CASE

Stand		2010	2025	2035	2055	2075	2085	2115	1995
120 year	*SEV Start*								1995
	SEV End							2115	
	Cash Flow	($62)	$304		$3,233		$5,697	$22,961	($263)
	Future	($10,463)	$24,535		$60,382		$24,624	$22,961	($91,882)
40 base	*SEV Start*								1995
	SEV End			2035					
	Cash Flow	($62)		$6,309					($263)
	Future	($211)		$6,309					($1,854)
80 year	*SEV Start*								1995
	SEV End					2075			
	Cash Flow	($62)	$290		$3,296	$16,035			($263)
	Future	($1,486)	$3,330		$8,746	$16,035			($13,052)

CASH FLOW INTENSITY CASE

Stand		2010	2025	2035	2040	2045	1995
40 base	*SEV Start*						1995
	SEV End			2035			
	Cash Flow	($62)		$6,309			($263.34)
	Future	($211)		$6,309			($1,853.91)
40 high	*SEV Start*						1995
	SEV End			2035			
	Cash Flow	($62)	$371	$5,833			($263)
	Future	($211)	$604	$5,833			($1,854)
50 high	*SEV Start*						1995
	SEV End					2045	
	Cash Flow	($62)	$329			$9,231	($263)
	Future	($344)	$874			$9,231	($3,020)

NET PRESENT VALUE (5 % discount rate)

Stand	SEV
120	($153)
40	$463
80	$39

Stand	SEV
40 base	$463
40 high	$484
50 high	$404