AN ABSTRACT OF THE THESIS OF

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This project was a part of larger work that compared major factors controlling patterns of carbon dynamics in two regions of the globe, the Pacific Northwest, USA and northwestern Russia. It was funded through the NASA foundation (grant # NAG5-6242).

Human economic activity is causing the release of pollutants such as carbon dioxide. The increased concentration of pollutants in the atmosphere is thought to cause greenhouse effect, in other words – the warming of the earth and lower atmosphere. Different methods are proposed to reduce concentration of greenhouse gases (GHG) in the atmosphere. Some involve development of more clean technologies. Some involve reductions in the use of fossil fuels. Another possibility is to store carbon (C) as live biomass. Plants use C for growth and development. Using forests to sequester C is one strategy for mitigating effects of GHG emissions. There are many methods in forestry to grow trees and produce wood products. Some of them include clearcutting, thinning, fertilizing, burning, and partial cutting.

This project had three purposes. First, was to investigate the effect of a wide variety of silvicultural treatments on C storage and the economic value of harvested forest products. We measured economic value as soil expectation value. Second, was to use Data Envelopment Analysis to determine the efficient set of treatments, which make up the Production Possibility Frontier (PPF) in terms of C and economic value. Third, was to use the PPF to measure the marginal cost of carbon storage in moving from high SEV and relatively low C storage to lower SEV and relatively high C storage.

C storage and timber harvest were simulated using the STANDCARB model for forest types common in north-western Oregon with two tree species, Douglas fir (*Pseudotsuga menziesii*) and Western hemlock (*Tsuga heterophylla*). Fifty silvicultural regimes were investigated. They included clearcutting with rotations of 50, 70, 90, 110, 130, and 150. Each of the six rotation ages had eight combinations of silvicultural treatments consisting of artificial and natural regeneration, growth enhancement (GE) and thinning. Two partial cutting regimes: group selection and single-tree selection were also used in the analysis.

C storage was calculated for every output year of each model run as a sum of live, dead, and stable C. C storage for each silvicultural regime was measured as the average over five full rotations from the steady state portion of the run.

The analysis showed that average C increases with rotation age from 335.99 MgC/ha with 50-year rotation with natural regeneration and thinning to 826.36 MgC/ha with 150-year rotation with artificial regeneration and GE. The use of artificial regeneration compared to natural regeneration gave a 20-30 MgC/ha improvement for all regimes.

The total harvest from thinning and clearcutting over the rotation period averaged for several runs varied from 505.34 m3/ha (with 50-year rotation no treatment) to 1782.24 m3/ha (with 150-year rotation with GE and thinning). The use of artificial compared to natural regeneration gave a 20-50 m3/ha increase in harvest for all regimes.

SEV is the present value of net revenues from perpetually growing tree crops following the specified regime. It measures the economic value of each regime. Generally, SEV has a negative correlation with rotation length. Using a 3.5 percent

real discount rate, the maximum SEV ($7904.3/hectare) was obtained from 50-year rotation with artificial regeneration, GE and thinning. In contrast, SEV for 130-year rotation with artificial regeneration was only $446.68/hectare.

Using Data Envelopment Analysis (OnFront software) we found that 8 of the 50 regimes investigated were efficient in their ability to store C and produce economic value. The efficient regimes included 50, 110, 130 and 150-year rotations with artificial regeneration, GE and thinning; 110, 130 and 150-year rotations with natural regeneration, GE and thinning, and the 150-year rotation with natural regeneration and GE.

When regimes with GE were excluded, we found 7 efficient regimes: 50 and 150-year rotations with artificial regeneration and thinning, 50, 110, 130 and 150-year rotations with natural regeneration and thinning, and the 150-year rotation with natural regeneration.

The marginal cost of C storage is the SEV lost per unit of C due to change in silvicultural regimes that results in increase of average C stored. Marginal cost analysis indicated that marginal cost values were similar for regimes with GE and without. As C storage increased, the marginal cost generally increased. The increase in C storage from 428 MgC/ha to 589 MgC/ha implied a marginal cost of $13.28/MgC. In case of increasing C storage from 683 MgC/ha to 802.7 MgC/ha, the marginal cost would increase to $32.79/MgC.

Measuring Costs of Sequestering Carbon in Forest Stands with Different Management Regimes in Western Oregon

by

Olga A. Zyrina

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Olga A. Zyrina, Author

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1 INTRODUCTION

1.1 The problem of global warming

Human economic activity causes the release of atmospheric trace gases – mainly carbon dioxide, methane, nitrous oxide and chlorofluorocarbons. These gases tend to block the emission of heat from the earth's surface and are said to result in the so-called greenhouse effect and global warming (Pearce and Turner, 1994). Carbon dioxide is produced when fossil fuels are burned and when forests are cut and burned. Methane and nitrous oxide are emitted from agricultural activities, changes in land use, and other sources. Concentrations of carbon dioxide in the atmosphere have risen by 25 percent over the last two hundred years and the trend is upward. Currently, fossil fuel burning accounts for about 80 percent of annual carbon dioxide emissions, but deforestation also plays an important part.

Climate models predict that the global temperature will rise by about 1-3.5°C by the year 2100. This projected change is larger than any climate change experienced over the last 10,000 years (UNFCCC, 1999).

Climate change is likely to have a significant impact on the global environment. In general, the faster the climate changes, the greater will be the risk of damage. The mean sea level is expected to rise 15-95 cm by the year 2100, causing flooding of low-lying areas and other damage. Climatic zones (and thus ecosystems and agricultural zones) could shift towards the poles by 150-550 km in the mid-latitude regions (UNFCCC, 1999). Forests, deserts, rangelands, and other unmanaged ecosystems would face new climatic stresses. As a result, many will decline or fragment and individual species will become extinct. The rate and magnitude of possible climate change, as well as the physical impacts associated with such change, are uncertain. There is, however, an emerging consensus that policies to stabilize or reduce emission of greenhouse gases (GHG) – which include carbon dioxide (CO_2) and other radiatively important trace gases – should be explored (U.S. EPA, 1995).

Responding to concerns that human activities are increasing concentrations of GHG in the atmosphere, most nations of the world joined together in 1992 to sign the United Nations Framework Convention on Climate Change (UNFCCC) where they agreed to voluntary actions to reduce GHG emissions (Fletcher, 2000). When it appeared that nations would fail to meet voluntary emission limits, parties to the UNFCCC entered into negotiations on a protocol to establish legally binding emissions limitations. These negotiations resulted in the 1997 Kyoto Protocol to the UNFCCC, in which the parties agreed to binding limitations of GHG for the 38 developed countries and economies in transition. This treaty would commit the United States to a target of reducing GHG by 7% below 1990 levels during a "commitment period" between 2008-2012.

As it is stated in the Climate Change Action Plan (U.S. Department of State, 1997), investing in energy efficiency is the most cost-effective way to reduce CO_2 emissions. Another considered option is C sequestration in forests. The United States has already taken significant steps to protect carbon sequestered in forests. Lower harvests in old-growth forests help to prevent CO_2 emissions. The shift toward ecosystem management also favors timber harvest methods that remove less timber, and helps to retain carbon (C) on forest lands. Such actions as reducing depletion of nonindustrial private forests and tree planting on poorly stocked and nonstocked nonindustrial private forest land are considered by the Climate Action Plan for increase of C sequestration in U.S. forests.

1.2 Place of forest ecosystems in the problem

Vegetation and soil contain about three times as much C as the atmosphere. Therefore, terrestrial ecosystems offer an opportunity to absorb and store (sequester) a significant additional amount of CO_2 from the atmosphere (U.S. EPA, 1995). Forest ecosystems play a significant role in storing C. The world's forests cover some thirty-four million square kilometers or roughly 27 percent of the ice-free land surface of the earth. Forests supply ecosystem services of numerous sorts. They stabilize landscapes, protect soils, preserve watershed functions, modulate climate at local and regional levels, and at planet-wide level, they help to contain global warming by virtue of the C stocks in their plants (especially trees) and soils (Daily, 1997).

The world's forests contain vast quantities of C, stored in forest soils, live tree and plant tissues, dead wood, branches, and plant litter. It is determined now that C comprises 48% to 52% of live tree biomass (Harmon, M.E. June 2, 2000. Personal communications). Also, plants use C in the photosynthesis process. It is also known that release of C takes place through respiration of live plants as well as respiration and decomposition processes that take place in soil, small and large woody debris, and plant litter.

The growing stock of the Pacific Northwest forests and therefore its potential to store C is several times higher than growing stock of forests around the world. C densities were measured in 43 forest stands throughout Oregon and Washington (Smithwick et al., Submitted). In the Oregon Cascades, the total stand C densities vary from 437.9 to 1073.1 MgC/ha with the mean of 807.6 MgC/ha. Compared to other regions of the world, the average potential C storage for PNW forest stands is about 2 times higher than for tropical forests, and about 1.5 times higher than for boreal forests.

The Pacific Northwest is also a major region for timber production and logging, which have the potential of significantly decreasing C stores (Krankina and

Harmon, 1994). The level of C sequestered by a forest landscape depends on silvicultural practices applied there. The three factors that can be the most crucial for storing C are rotation length, amount of live mass harvested, and amount of detritus removed by site preparation (Harmon and Marks, in review).

Changes in silvicultural practices affect the level of C stored by forest. The conversion of 5×10^6 hectares of old-growth forests to younger plantations in western Oregon and Washington in the last 100 years has added 1.5×10^9 to 1.8×10^9 megagrams of C to the atmosphere (Harmon et al., 1990).

The potential for a landscape to store C is primarily a function of frequency and severity of disturbance. Using a simulation model, the maximum amount of C stored by a landscape was calculated to be 875 Mg/ha (100%) for a landscape consisting of entirely old-growth forests (Harmon and Marks, in review). The landscape with the minimum C store (15% of maximum) was an agricultural row crop system, which consisted mostly of stable soil stores and a minimum of live vegetation. The highest C store was for burned forest protected from either low or moderate severity fire; these landscapes stored between 91.8 to 92.9% of maximum. The results of the partial cutting experiment strongly suggests that harvesting a smaller area more frequently results in more C stores than cutting the entire area once. By harvesting 10% of the area every 10 years a landscape would store 68% of the maximum. This compares to 57% for the more traditional 100% cut on a 100 year rotation.

Increasing forest area and enhancing the productivity of existing forests are two options being considered by U.S. policy makers to mitigate global climate change through the sequestration of C in forests and forest products. Since forests sequester C from the atmosphere as part of the growth process, any increase in forest biomass constitutes a sink that will help to reduce the build-up of atmospheric carbon dioxide (Alig, 1997).

1.3 Justification and expected accomplishments

Forests are a critical part of the C cycle. Their management has important implications for the concentration of the greenhouse gas carbon dioxide in the atmosphere. Forests and their associated detritus and soils have very large potential to store C. Harvesting of forests for commercial forest products and the removal of non-commercial products such as fuelwood reduce the amount of C stored in forests. Other management activities such as afforestation, fertilization, and protection from fire and insects may increase the amount of C stored by forests. The effect of other common practices such as thinning and species replacement are uncertain as past research on these practices has focused on harvestable volume, costs and economic value, not C sequestration.

The International Panel on Climate Change (IPCC) includes the analysis of possible costs and benefits as one of the important factors that need to be taken into account in the evaluation of projects and public policy issues related to climate change (Bruce et al., 1995). Economic cost benefit analysis can help guide decision-makers intent on global agreements to manage C emission. The calculation of relative marginal costs of C storage by treatment type, level, and location may be useful in choosing the least costly regional and global policies to manage C stores.

2 LITERATURE REVIEW

2.1 Forest management practices and their potential in storing carbon

Virtually all commercial forests in western Oregon are managed under the even-aged silvicultural system (Svicarovich, 1999). Clearcutting is the primary method of harvest on private land in western Oregon. During the period from 1984-86 through 1994, more area was clearcut in the 50-year age class (trees 45-55 years old) than in any other single age class. The survey of foresters in Oregon showed that future clearcut ages in western Oregon will vary from 35 to 65 years (Lettman and Campbell, 1997).

Using longer rotations is one of the possibilities to increase the amount of C stored in forests (Curtis and Marshall, 1993). There are several arguments for using longer rotations. Extended rotations (combined with thinning and other cultural practices) would mean larger trees, higher quality wood, higher values per unit of volume (and, therefore reduced direct management and harvesting costs), longer thinning cycles, and associated with all this increased C storage. On the landscape level, the use of longer rotations would reduce land area in the regeneration and early developmental stages and hence, reduce slash burning and herbicide use.

The yield of merchantable timber volume by stands can be enhanced by thinning or temporary reduction in stand density that enhance diameter growth (Smith, 1986). Thinning performs 3 economic functions – harvesting trees that would otherwise succumb to suppression, accelerating the timing of cash flows from the stand, and increasing the piece size of the remaining trees. These benefits are purchased at the cost of a possible reduction in final harvest volumes (Binkley et al., 1997). Other advantages of thinning include the opportunity to change stand composition to prepare for the establishment of new crops and reduced risk of damage or destruction by insects, disease, fire, or wind (Smith et al., 1997).

Depending on tree growth, owners may perform a precommercial thinning at age 10 to 20 years leaving 250 to 300 trees per acre. At 20 to 30 years, an owner may conduct the first commercial thinning, a harvest in which trees now 8 or more inches in diameter can be sold for conversion into studs and chips. Some owners continue to perform commercial thinnings until trees are sufficiently mature to harvest in a clearcut (Svicarovich, 1999).

Examples in the literature show that thinning at age 30 and 45 can lead to high yields and development of good quality in residual dominant trees (Newton and Cole, 1987). Thinning at age 48 with removal of two-thirds of the standing volume (to 50 stems/acre) on Black Rock plot 31 in Oregon Coast range resulted in steadily increasing growth that continues to accelerate at age 81. This 81-year old stand produced about 1.25 times the cubic volume of two 40-year rotations. But, in terms of value production the 81-year old stand had a 2:1 advantage (Curtis and Marshall, 1993).

The investment in thinning made at the appropriate time could increase the net return from the whole crop. Economic analyses have repeatedly shown that precommercial thinning often is the most rewarding long-term investment that can be made in silvicultural treatment (Smith et al., 1997). However, in many cases precommercial thinning produces felled trees that are too small to be salable. In contrast, commercial thinnings yield logs large enough to be sold (Klemperer, 1996).

Planting can substantially increase wood production. It also provides greater control of spacing and composition of the next stand, influences quality and genetic composition, reduces the period between harvest and reestablishment of tree cover, and reduces the exposure of mineral soil (required for natural establishment of some species) (DeBell and Curtis, 1993).

Fertilization allows trees to establish and grow faster increasing the storage per hectare by the time of final harvest. Nitrogen is the most widely used macronutrient fertilizer in forestry, and although recent increases in the cost and decreases in the availability of nitrogen fertilizers raise question about the future of large-scale forest fertilization, the use of fertilizers in forestry will probably grow as the value of forest products increases (Kimmins, 1987).

2.2 Costs of silvicultural practices

In this study we compare costs of sequestering C by different silvicultural regimes. This requires that we estimate the costs of various silvicultural treatments. We obtained cost estimates from the existing literature and from personal communications with foresters in Oregon. All costs prior to year 1999 were converted to 1999 costs using the producer price index (Bureau of Labor Statistics, 2001).

Planting is one of the most expensive steps in silviculture. The costs of artificial regeneration significantly vary depending on factors such as cost of labor, capital, nurseries, planting stock, equipment, site preparation, and treatment after planting (Smith et al., 1997). However, the benefits of using artificial regeneration can be very high.

Planting cost estimates for Western Oregon vary from \$158 to \$300/acre. Mark Gourley gave an estimate for planting of \$158 to \$280/acre including the cost of seedlings \$0.25-0.45/tree and labor costs \$0.20-0.25/tree for Starker Forests (Gourley, M. July 1, 1999. Personal communications). Timberland Regeneration Enterprises provided another estimate for the cost of planting in Western Oregon of \$250-300/acre (Maganas, H. June 23, 1999. Personal communications). Dan Newton from Roseburg

Forest Products suggested to use the planting cost of $200/acre (Newton, D. July 1, 1999. Personal communications). The Blodgett Forest Plan assumes planting costs of $200 to $250/acre (Sessions et al., 1999).

The cost of artificial fixation of nitrogen for fertilizer in terms of both money and energy is high. However, nitrogen is so crucial for forest growth that spectacular effects can result from reducing the chronic deficiencies (Smith et al., 1997). The cost of fertilization conducted the same year as planting is about $50-55/acre including $35/acre for labor and $15-20 for fertilizer (Capanna, M. Miller Timber Services. June 22, 1999. Personal communications). Fertilization may cost $60 to $125/acre from the estimate by Mark Gourley from Starker Forests (Gourley, M. July 1, 1999. Personal communications). The Roseburg Forest Products company has estimated fertilization at $65/acre (Newton, D. July 1, 1999. Personal communications). Considering the above information, the range of values for fertilization is $50 to $125/acre.

Commercial thinning costs were studied in young forests containing western hemlock and Sitka spruce in the Oregon Coast Range (Kellogg and Olsen, 1986). The stand was precommercially thinned at age 15. Harvesting cost and stand damage during logging were analyzed for commercial thinning at the age 32. The average stand dbh before thinning was 13.4 inches and average tree height was 74 feet. The stand was commercially thinned using three prescriptions, (50-60% volume removal): strip thinning, narrow spacing thinning, and wide spacing thinning. Total harvesting costs included felling, yarding and loading, and hauling. The results of the study indicated that total harvesting costs for strip thinning per thousand board feet (Mbf) were $264.6/Mbf, $315.6/Mbf for narrow spacing, and $280.01/Mbf for wide spacing. The selective thinning operation caused more residual stand damage than the strip treatment.

Thinning and clearcutting stump-to-mill logging costs were developed for the Blodgett Tract plan comprised by the group of researchers at the Oregon State

Univeristy (Sessions et al., 1999). A set of log prices and harvest costs was created to be used with the harvest scheduling model. Skyline yarding costs were computed using the USDA Forest Service Region 6 skyline appraisal model. Costs included felling, delimbing, bucking, yarding, loading and hauling. Skyline stump to mill costs for thinning harvest units varied from $125.12/Mbf to $339.9/Mbf as average log volumes were varied between 70 and 340 board feet, and as cut volumes were varied between 3 and 20 Mbf/acre. Skyline stump to mill costs for clearcut harvest units varied from $107.13/Mbf to $139.17/Mbf as average log volumes varied from 130 and 450 board feet. Sale preparation and administrative costs excluding office overhead costs were estimated to be $17.57/Mbf on clearcut harvest units and $42.20/Mbf on thinning harvest units.

A study in the Oregon Coast Range was conducted to evaluate the economic impact of proposed Oregon forest practices rules on industrial forest lands (Olsen et al., 1987). Three scenarios were modeled in two stands of small timber (with volume 36 Mbf/acre and an average dbh=18 inches) and large timber (with volume 60 Mbf/acre and an average dbh=28 inches). Harvest systems included felling, ground based and cable yarding, road and landing changes, landing construction, and loading and hauling. The results indicated that landowners' costs would be significantly greater with a more restrictive regime of establishing riparian buffers. Total harvesting costs for scenario 1 were larger in the small timber stand ($151.93/Mbf) than in the large timber stand ($96.06/Mbf).

Logging planning, felling, and cable yarding costs were determined for five group-selection treatments and a clearcut in a 90 yr old Douglas fir stand in western Oregon (Kellogg et al., 1996a). Average dbh was 18 inches, average height 94 feet, and average volume per acre was 36.1 Mbf.
Five group-selection treatments included:

- Strips, 2-3 acres each, with parallel skyline roads;

- Rectangular patches, 0.5 acres each, with central landing and fan skyline roads;
- Rectangular patches, 1.5 acres each, with central landing and fan skyline roads;
- Wedges, 2-3 acres each, with central landing and fan skyline roads;
- Rectangular patches, 0.5 acres each, with parallel skyline roads.

Total logging costs combined logging planning, felling, and yarding costs. The clearcut treatment was the least expensive with costs of $71.97/Mbf. Costs of the group-selection treatments were 7.3 to 31.5% higher than the clearcut. The wedge treatment was the least costly of the five group-selection treatments ($77.22/Mbf), while the 0.5 acre fan roads treatment was the most costly ($94.67/Mbf). Yarding cost associated with road and landing changes, equipment moving, set up, and tear down allocated over different treatment volumes removed had the biggest influence on total cost for each silvicultural treatment.

Harvest costs were estimated for New Forestry silvicultural prescriptions designed for application on national forest lands in western Montana (Keegan et al., 1995). Costs were developed for three major logging systems (tractor with hand-felling, tractor with mechanical-felling, and uphill skyline with hand-felling). Average dbh ranged from 7 inches to 16 inches. Volume per acre ranged from 7 Mbf to 15 Mbf. Nine forest practices were used to manage stands (data on costs was surveyed from 25 logging companies in western Montana). The difference between clearcutting and partial cutting costs was insignificant with tractor ground logging system varying from $88.56/Mbf to $105.67/Mbf. Stump to loaded truck logging costs for group selection harvest system was $223.42/Mbf and for individual tree selection system $172.1/Mbf.

A summary of silvicultural costs from surveyed sources is presented in Table 2.1. To make costs comparable, a $30/Mbf hauling cost (the most common hauling cost presented in literature) was included in the cost for each harvesting method.

Table 2.1. Summary of silvicultural costs from surveyed sources (1999 dollars).

Type of management	Cost	Source
Planting	$158 to $280/acre	Gourley, M. July 1, 1999.
	$250-300/acre	Maganas, H. June 23, 1999.
	$200/acre	Newton, D. July 1, 1999
	$200 to $250/acre	Sessions et al., 1999
Fertilization	$50-55/acre	Capanna, M. June 22, 1999.
	$60 to $125/acre	Gourley, M. July 1, 1999.
	$65/acre	Newton, D. July 1, 1999.
Commercial thinning	$264.6 to $315.6/Mbf	Kellogg and Olsen, 1986
	$125.12 to $339.9/Mbf	Sessions et al., 1999
Clearcut harvest	$107.13 to $139.17/Mbf	Sessions et al., 1999
	$96.06 to $151.93/Mbf	Olsen et al., 1987
	$101.45/Mbf	Kellogg et al., 1996a
Partial harvest (groups)	$106.72 to $124.18/Mbf	Kellogg et al., 1996a
Groups	$223.42/Mbf	Keegan et al., 1995
Single-tree	$172.1/Mbf	
Administrative	$17.57/Mbf on clearcut	Sessions et al., 1999
	$42.20/Mbf on thinning	

2.3 Marginal costs of storing carbon

Various sources in the literature present marginal costs of storing C that significantly differ from each other.

Dixon et al. (1993) reported that in boreal forest systems, natural and artificial reforestation have the initial cost of C sequestration of $5.3 ($4.2-11.6)/MgC and $8.5

(\$3.2-28.5)/MgC at C storage values of approximately 17 Mg/ha and 39 Mg/ha respectively. Reforestation, afforestation, natural regeneration, and silvicultural practices were found to be the least expensive forest management options for C sequestration within temperate regions. At a median cost of about \$369.6/ha, silvicultural treatments such as thinning and fertilization can enhance C storage in temperate forests with the initial cost of \$13.7 (\$3.2-166.9)/MgC. The range of costs for forest management options within tropical latitudes was very wide from approximately (\$1.6-38)/MgC for thinning and fertilization at a sequestration value of 59 MgC/ha to less than \$10.6 (\$2.1-27.5)/MgC for reforestation and agroforestry at a sequestration value of about 100 MgC/ha.

A case study from a boreal forest in Norway (Hoen and Solberg, 1994) indicated that up to 80 percent increase in the present value of the flow of net CO_2 fixation (NPV_{CO2}) can be reached at a marginal cost (shadow price) below US\$21.9/ton of NPV_{CO2} at a real rate of discount of 4, 5, and 7 percent. The corresponding marginal cost measured per ton C was calculated to be US\$82.3. With the lower real rate of discount of 3 and 2 percent, the marginal costs were significantly higher, but by lowering the level of NPV_{CO2} to 60%, the marginal costs were decreased to US\$8.3/ton NPV_{CO2} with a 3% rate and US\$27.1/ton NPV_{CO2} with a 2% rate.

Grassland ecosystems were considered as another C pool. Grassland soils sequester large quantities of C as soil organic matter, which are rapidly transferred into the atmosphere when plowed and converted into agricultural land. In comparison with other ecosystems such as forests, grasslands store most of their C belowground. The value of C sequestration in grasslands was calculated to be \$196.6/hectare with a range between \$157.3 and \$393.2/hectare with the cost of \$19.7/MgC (Daily, 1997).

Afforestation (planting trees) of marginal agricultural lands to sequester C is another strategy for mitigating GHG emissions. Social costs of sequestering C in tree plantations on U.S. agricultural land were calculated for three scenarios with various restrictions on tree planting. The marginal cost varied from \$19.5/ton of C (with total of 140×10^6 tons of C sequestered) to \$211.6 (with total of 700×10^6 tons of C sequestered) (Adams, et al. 1993). In a similar study by other authors marginal costs varied from \$17.9 to \$37.5/MgC for the same amounts of total C sequestered (Moulton and Richards, 1990).

3 METHODS

3.1 STANDCARB model

The amount of C sequestered by forest stands was calculated by STANDCARB, a stand scale model developed by Harmon et al. (1996). The STANDCARB model is designed to simulate the dynamics of living and dead pools in a forest stand. The current version of the model is parameterized specifically for stands in the Pacific Northwest. This model is a hybrid between a gap succession model and an ecosystem process model. The purpose of the STANDCARB model is to explore the effects of species succession and disturbance severity (e.g., clear-cut versus thinning or partial cut) on C sequestration. This model considers three life forms (herbs, shrubs, and trees), which grow in a stand comprised of 100-500 cells that interact through shading. The model simulates C stores in 7 live pools, 6 corresponding detritus pools, and three stable C pools. In addition to including three life forms, the model includes tree species succession, and allows for thinning or partial stocking of trees.

In STANDCARB, a stand is represented by replicate cells, which are then averaged to predict stand level values. In our simulations, we used an area represented by 100 cells (10 by 10). With one cell being 15 meters wide, the 10 by 10 cell area equals 2.25 hectares, or about 5 acres. The selection of a 15-meter wide cell was based on the diameter of the crown for the mature Douglas fir tree (Paine and Hann, 1982).

Stands simulated in STANDCARB represent a mixture of two species with Douglas fir (*Pseudotsuga menziesii*) being a dominant species and Western hemlock (*Tsuga heterophylla*) as codominant species. This type of stand is typical for forest conditions in northwestern Oregon.

The STANDCARB model requires input on amount of timber harvested and time when this treatment would be done. In addition, the user determines the percent of timber harvested, percentage of timber removed from the forest unit, type of regeneration and thinning, and rotation age. Other background conditions for the selected area include climate, species, growth, decomposition and mortality rates. Input parameter files used in the model runs for this study are presented in Appendix A.

The data produced by the STANDCARB model was converted to Excel files for calculation of average values and data necessary for economic analysis. The information on living and dead C stores was obtained from the STANDCARB model outputs. Two output files produced by the STANDCARB were mainly used for calculations. The Total.out file has the totals of C stores and the volume harvested. It can be used for assessing overall effects of treatments on stores of organic matter or C. This file gives information on mean total live C for all the cells (Mg/ha). This includes boles, branches, leaves, fine roots, and coarse roots for herbs, shrubs, upper trees, and lower trees. The mean of the total dead C for all cells (Mg/ha) includes dead foliage, dead fine roots, dead coarse roots, dead branches, dead sapwood, dead heartwood, and stable soil. The total dead C for all cells except for the stable soil (Mg/ha) is the fraction of dead material that is expected to change significantly with varying silvicultural treatments. The file also calculates the mean cubic volume, excluding bark, of upper and lower trees (cubic meters/ha) and the mean harvested volume during each year (cubic meters/ha).

The file Volume.out gives the cubic volume and the amount of volume harvested in a given year. The species composition, mean age and height of the harvested upper tree layer is also received from this file for use as an indicator of the prices that can be obtained for harvested volumes.

3.2 STANDCARB model calibration

3.2.1 Standcarb calibration for volume growth over time

The model parameter files were calibrated to adjust the model behavior in a manner consistent with data from Western Oregon and Washington. The real data on Douglas fir growth in Oregon and Washington were used to calibrate growth (McArdle and Meyer, 1930). The data gave net cubic foot volume of wood per acre for 14 Site indexes (SI, height in feet at 100 years). To make the data comparable to STANDCARB, the cubic foot volume was converted into net cubic meter volume per hectare.

A growth curve was constructed based on this data from growth and yield tables (volume in cubic feet over time). In STANDCARB, the data on volume in cubic feet were obtained from the Total.out file. Growth over time produced by STANDCARB was then compared to real data.

To fit the STANDCARB growth curve over real data growth curve, necessary adjustments were made in Growth.prm and Siteindex.prm files. If the STANDCARB volume curve was lower than real data, the value for the site index in the Siteindex.prm file was increased and vice versa.

The maximum rate of foliage production (FoliageProdRateMax) value helps to regulate early rate of growth. For calibration purposes it was adjusted for Douglas fir (from 0.5 to 0.85) and Western Hemlock (from 0.5 to 0.6) in the Growth.prm file.

3.2.2 Model calibration for carbon pools

Average C pools measured in 14 old-growth stands in the Oregon Cascades (Smithwick et al., Submitted) were compared to C pools produced by the STANDCARB for similar growth conditions. The model was run for 1000 years to bring C balance to a steady state condition. The average value was calculated from year 300 to 1000 for every C pool.

Because ecosystem elements included in the C pools in STANDCARB differed from those in the Oregon Cascades data by Smithwick et al. (Submitted), some of the C pools in STANDCARB were combined to make this comparison. Table 3.1 shows the assignment of C pools in STANDCARB to Oregon Cascades data by Smithwick et al. (Submitted).

Average C values were compared by dead and live C pools. The parameter values were adjusted for Douglas fir and Western hemlock in Growth.prm, Decomp.prm, Mort.prm, EcoRegion.prm, and DecayPool.prm files.

Table 3.1. C pools in STANDCARB and Oregon Cascades data.

Oregon Cascades C pools	STANDCARB files	STANDCARB C pools
Live branch	Live.out	Branch
Foliage	Live.out	Foliage
Stem wood	Live.out	Sapwood+Heartwood+Heartrot
Fine roots	Live.out	Fine roots
Coarse roots	Live.out	Coarse roots
Fine woody debris	Dead.out	Dead branch
Dead roots	Dead.out	Dead fine + coarse roots
Forest floor	Dead.out Stable.out	Dead foliage + + Stable foliage
Rotten wood	Stable.out	Stable wood
Soil	Stable.out	Stable soil
Logs	Deadwood.out	Non-salvagable logs
Snags	Deadwood.out	Non-salvagable snags

3.3 STANDCARB model runs and outputs

Part of our analysis studied the effect of clearcut rotation ages on C sequestration using 6 prescriptions from 50-year to 150-year rotations by 20-year increments. For each rotation we used four combinations of silvicultural treatments that included planting, growth enhancement, and thinning. The following thinning regimes were applied based on common practices used in Oregon:

50-year rotation with commercial thinning at age 30;
70-year rotation with commercial thinning at age 30 and 45;
90-year rotation with commercial thinning at age 30, 45, and 60;
110-year rotation with commercial thinning at age 30, 45, 60, and 80;
130-year rotation with commercial thinning at age 30, 45, 60, 80, and 100;
150-year rotation with commercial thinning at age 30, 45, 60, 80, and 120.

The growth enhancement (GE) treatment may be interpreted as fertilization, seedling improvement from best trees, or genetic modification. Growth enhancement in STANDCARB was modeled by the increase in Site Index (from 3 Medium with Max Density of 560000 to 2 Medium with Max Density of 757000), which gave a similar to the use of fertilization percent increase in growth. The first four series were based on rotations with planting (artificial regeneration).

1. Vary rotations from 50 to 150 years with planting, GE, thinning.
2. Vary rotations from 50 to 150 years with planting, GE, but no thinning.
3. Vary rotations with planting, no GE, but use thinning.
4. Vary rotations with planting, no GE and no thinning.

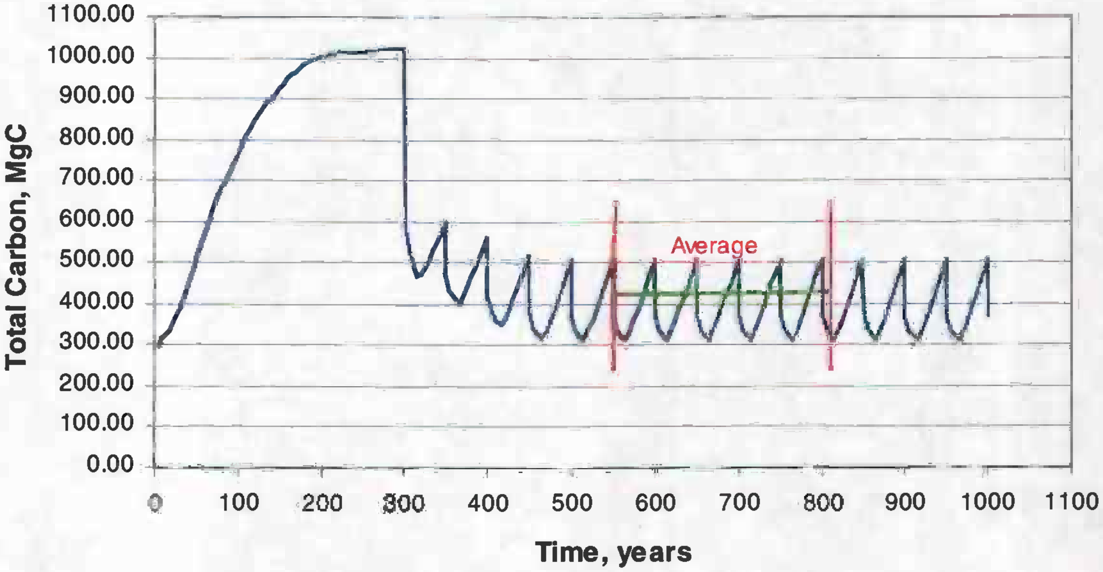
Second four series were based on rotations with no planting (natural regeneration):

5. Vary rotations with no planting, but use GE and thinning.
6. Vary rotations with no planting, but use GE, and no thinning.
7. Vary rotations with no planting, no GE, but use thinning.

8. Vary rotations with no planting, no GE and no thinning.

Therefore, for every rotation modeled, we had 8 different prescriptions; that brings the total number of regimes to 48.

Figure 3.1. Example of 5 steady state rotations used in calculation of the average total C.



For each regime we ran STANDCARB for 300 years without treatment for model calibration, then the stand was clearcut at 300 years to set the beginning point for all regimes. The silvicultural regime was then applied for about 7 to 10 rotations, in order to get 5 rotations from the steady state part of the run (Figure 3.1).

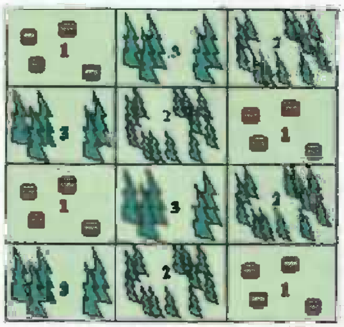
Because in STANDCARB each model run starts with random number (seed), for the same silvicultural regime the runs differed with the coefficient of variation of

0.3 to 1%. To account for this difference, the model was run 5 times for each silvicultural regime to calculate the average.

Another strategy for storing C is uneven-aged management. Uneven-aged silviculture can be useful when an owner wants to produce a steady and predictable flow of logs while maintaining forest complexity and aesthetic appearance. Other possible benefits include lower and more evenly spread regeneration costs, the opportunity to cultivate larger trees and higher quality wood, and improved habitat for some wildlife species (Svicarovich, 1999).

There is no single recommendation on how to create a group selection cut. Based on the reviewed literature (Kellogg 1996a, Keegan 1995, Kohm 1997), two selective cutting systems of group-selection and single-tree selection were modeled in comparison to clearcutting.

Figure 3.2. Logging layout for the group-selection treatment.



1 – first entry removal;
2 – second entry removal (30 years after 1st entry);
3 – third entry removal (30 years after 2nd entry).

For the group selection stand grows to 90 years when the first entry removal occurs. The treatment is designed for a 3-entry cutting cycle with 30 years between entries similar to work by Kellogg (1996a). Logging layout for this treatment is shown on Figure 3.2. The harvest patches are of rectangular shape about 0.5 acers in size.

With the cell size in STANDCARB being 15 by 15 meters, one patch equals 3 by 3 cells, or 2025 square meters (0.51 acers).

To model a group selection cut, the total number of cells used for STANDCARB modeling was increased from 100 to 108 to include 12 patches. Every 30 years 36 cells (4 patches) or one third of the modeled area were planned for harvesting.

For group-selection cut we run STANDCARB for 300 years without treatment for model calibration. Then, the stand was clearcut at 300 years to set the beginning point for all regimes. The first entry was made after 90 years of stand growth, with second entry removal in 30 years after first entry and third entry removal in 30 years after second entry. The silvicultural regime was then applied with clearcutting one third of a stand every 30 years until the model reaches a steady state condition.

Single-tree selection cutting is the classic type of uneven-aged silviculture and management (USDA, 1976). It consists of the removal of trees throughout several or all diameter classes on an individual basis, leading to the formation of a stand containing an intimate mixture of size and age classes. Selection of trees to be removed is based on the characteristics of the individual trees in relation to the stand structure goals established for regulation. Trees removed are usually isolated from one another, but if several removal trees happen to occur together, this is still single-tree selection.

If the suggested cutting cycle for selection management is 20 years (USDA, 1976) and we select a 100-year rotation age, then the stand is entered 5 times with the 20 percent of trees being harvested each time. For this regime the stand was clearcut at age 300 (to set starting point). The first single tree cut occured at age 50 years with following cuts being repeated every 20 years up to year 1030.

Two types of output were obtained from the STANDCARB model runs. The first was average total C amount from the Total.out file. The averages for live, dead, and stable C were first calculated for the five repeated model runs. C output in the Total.out file was presented every five years. STANDCARB produces two output values (before and after treatment) for the year when treatment is applied. In this case, the average for that year was calculated and used in calculation of live, dead, and stable C averages. The total C is the sum of averaged live, dead, and stable C. To calculate total average C we used 5 complete rotations from the steady state part of the model run (Figure 3.1).

The second type of output from the STANDCARB model was information on timber volume harvested (cubic meters per hectare) at the specific year from the Volume.out file. This included the species harvested, the volume harvested and the height of harvested trees in meters. Volume information was used to calculate Soil expectation value (SEV).

3.4 Cost analysis

The next step of the analysis was to combine the information on C with costs of various forest treatments. Costs were obtained from journal articles, personal conversations and the Oregon Department of Forestry. These costs were usually presented in board feet per acre (bf/ac). The conversion from board feet to cubic meters depends on tree diameter. Diameters can be estimated from STANDCARB model outputs in Volume.out file, which gives volume harvested in cubic meters and average height in meters. Cubic meters can be converted to cubic feet using a factor of 35.32 cubic feet per cubic meter. The conversion factor from meters to feet is 3.281 feet per meter. The diameter in inches can be predicted from volume and height using cubic-foot volume tables for Douglas fir (USDA FS, 1955).

Table 3.2. Board foot to Cubic foot conversions based on diameter calculated from STANDCARB.

Year of treatment	30	45, 50, 60	70, 80, 90	100, 110, 120	130, 150
Board feet per Cubic foot	3.3	4.1	4.7	5.2	5.5

The following conversions from board foot to cubic foot were used in this project (Table 3.2). They are based on a board foot to cubic foot conversion table presented in Sessions et al. 1991.

3.4.1 Cost assumptions

With estimates of planting costs ranging from \$158 to \$300/acre (see Literature review section), the planting for this project was assumed to cost \$250/acre or \$617/hectare. The cost of growth enhancement treatment was based on reviewed cost of fertilization. For calculations, the GE cost was assumed to be \$60/acre or \$148/hectare.

The costs of commercial thinning and clearcutting for Oregon are presented based on volumes cut per acres and log size in the Blodgett forest plan (Sessions et al., 1999). They do not differ substantively from other sources reviewed (Kellogg and Olsen 1986, Olsen et al. 1987, Kellogg et al. 1996a). Harvesting costs for thinning and clearcutting increase with the smaller diameter trees and lower volume cut per unit area. Because STANDCARB does not produce diameter of harvested trees, the average diameter of harvested trees was estimated using volume tables (USDA FS, 1955) from tree volumes and heights found in Volume.out file.

Table 3.3. Costs of thinning and clearcutting.

Year of thinning	30	45, 60	80, 100	120
Thinning costs, $/Mbf	220	200	150	125
Year of clearcut	50, 60, 70	80, 90, 100	110, 120, 130	140, 150
Clearcut costs, $/Mbf	150	120	100	90

Using estimated diameter and harvested volumes, a set of assumed costs for thinning and clearcutting was produced based on Blodgett forest plan cost tables. Harvesting costs used for calculations in this project are presented in the Table 3.3.

Based on the Blodgett forest plan data, the administrative costs were assumed to be $17.57/Mbf for clearcutting and $42.2/Mbf for thinning.

To produce a set of harvesting costs for partial cutting, we used Kellog, et al. (1996a) comparison of costs for various thinning and group harvest regimes. These authors found that group-selection harvesting method with parallel skyline roads and 0.5-acre rectangular patches (similar to treatment simulated in STANDCARB in this project) had 18.5% higher harvesting costs than clearcutting costs. Based on this information, we assumed that group-selection harvesting costs were 20% higher than clearcut costs presented in the Table 3.3.

Kellogg et al. (1996b) showed that total harvesting costs decrease with higher thinning intensity. The results indicated that costs increased about 6% when less trees were harvested (about 25% residual trees) compare to heavier thinning (about 13% residual trees).

Table 3.4. Harvesting costs for group and single-tree selection.

Year of harvest (single-tree selection)	50	70	90, 100	110	130
Costs, $/Mbf	231	210	158	131	121
Year of harvest (group selection)		90	120	150	
Costs, $/Mbf		144	120	108	

Based on these suggestions we assumed that single-tree selection harvesting costs would be based on thinning costs presented in the Table 3.3 with 5% being added to adjust for lower intensity harvest.

Harvesting costs for partial cutting used in calculations in this project are presented in the Table 3.4. Percent adjustment similar to harvesting costs was used for administrative costs. Administrative costs for group selection harvest were assumed to be $21/Mbf and for single-tree selection harvest $44.31/Mbf.

Table 3.5. Log grade prices used in cost analysis in $/Mbf.

Log grade	Douglas fir	Western Hemlock
3P	830	
P		553
SM	715	510
2S	660	485
3S	610	444
4S	540	404
Utility		84

The Oregon Department of Forestry log prices for Douglas fir (Table 3.5) for domestically processed logs (delivered to a mill or "pond value") were calculated as an average for four quarters of the year 1999 (Corgan, 2000).

The assignment of log grades is usually based on log diameter and wood quality. Because it is impossible to estimated branch size and log taper from STANDCARB model output data, the log grades were roughly estimated based on personal experience of Dave Enck from ODF timber sales (Enck. D. October 16, 2000. Personal communications. Oregon Department of Forestry). The assumed distribution of harvest by log grades for various harvest years is presented in Table 3.6.

Table 3.6. Log grades distribution used in calculations.

Year of treatment	30	45-70	80-100	110-130	140-150
Log grade distribution	2S – 5% 3S – 80% 4S – 15%	2S – 15% 3S – 80% 4S – 5%	2S – 60% SM – 15% 3S – 25% (tree tops)	2S– 60% 3P – 10% 3S – 30% (tree tops)	2S– 60% 3P – 15% 3S – 25% (tree tops)

All costs and log prices used in the analysis are in 1999 US dollars.

3.4.2 Soil expectation value

We used Soil expectation value (SEV) to compare the economic values of the various silvicultural regimes. SEV is the present value of net revenues from perpetually growing tree crops according to the specified prescription (Davis and Johnson, 1987). The basic formula for SEV calculation is

$$SEV = \frac{a}{(1+i)^{w} - 1} \qquad (3\text{-}1)$$

Where a = future net income at end of one multiperiod payment interval as defined in Eq. (3-2)

w = rotation length, years

i = discount rate, %

The future net income a is calculated as

$$a = \sum_{t=1}^{w} R_t(1+i)^{w-t} - \sum_{t=o}^{w} C_t(1+i)^{w-t} \qquad (3\text{-}2)$$

Where period length = 1 year

a = future net income at end of one multiperiod payment interval

R_t = revenue received in year t

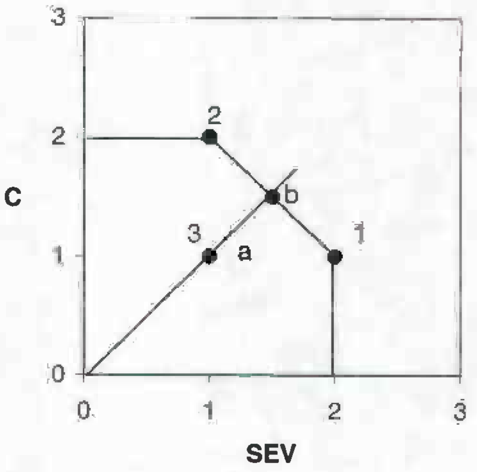
C_t = cost paid in year t

The real discount rate used for calculations in this project was 3.5 percent. SEV included costs of planting, GE, commercial thinning, clearcut or selective harvest and associated with them administrative costs. Net income at the end of rotation was based on assigned log grades and ODF log prices.

3.5 Data envelopment analysis

The set of relatively efficient silvicultural treatments was determined using Data Envelopment Analysis (DEA). DEA is a linear programming technique that identifies those treatments, which are inefficient relative to the best practice treatments. It establishes the production possibility frontier, or locus of efficient treatments, that shows the maximum amount of one output that can be produced, given a fixed amount of the other output. It is derived from the locus of production-efficient allocations.

Figure 3.3. The output measure of technical efficiency.



The production efficient point is an allocation of inputs such that the only way to increase the output of one commodity is to decrease the output of another commodity. In the present case, economic welfare from forest products was plotted on the horizontal axis, and average C sequestration on the vertical.

To illustrate DEA, Figure 3.3 shows three stylized regimes. Regimes 1 and 2 are efficient; they are on the boundary or best practice frontier of the technology. Observation 3 has the same inputs as 1 and 2 but produces less of both outputs. It is in the interior of the output set and is not productive as 1 and 2.

The relative technical efficiency of the observation 3 measured in a radial way is given by

$$0b/0a,$$

which is the ratio of maximum potential output (at b) to actual or observed (at a) output (Färe and Grosskopf, 2000). This measure is also called Farrell Output-Oriented Measure of Technical Efficiency. The output-oriented measure of technical efficiency is equal to one for efficient firms. Inefficient firms have output efficiency scores greater than one.

To conduct Data Envelopment Analysis we used OnFront (Färe and Grosskopf, 2000) computer software.

In this project, observation points were represented by regimes such as clearcutting, partial cutting, and treatments with planting and thinning. The objective of the project was to find the most efficient regimes. By efficient it is meant that more C cannot be stored without either sacrificing some harvest or incurring some additional costs. Several forest management scenarios were selected as the result of data envelopment analysis. The best scenarios can be suggested to guide decision makers in management of C emissions.

3.6 Marginal cost analysis

The marginal cost is the change in total cost (cost of forest treatment) due to the production of one more unit of output (Mg of C) as defined in Eq. (3-3). Cost per Mg of C was calculated as the present value (SEV) of a specific regime divided by average total C storage for that regime. The regimes for which marginal cost was calculated are the regimes selected by DEA, or those located on the production possibility frontier.

$$MC = \left| \frac{\Delta SEV}{\Delta C} \right| \qquad (3\text{-}3)$$

With the production of one additional output, marginal cost decreases at first and then increases (Hyman, 1991). The eventually increasing marginal cost of output reflects the law of diminishing marginal returns. As more of the variable input is hired, the extra output obtained eventually becomes smaller. This means that it eventually takes more of the variable input to produce each extra unit of output. Given the price per unit of the variable input, this implies increasing marginal cost. Considering the above information, we expected marginal cost to increase as the stand was managed for increasing amounts of C.

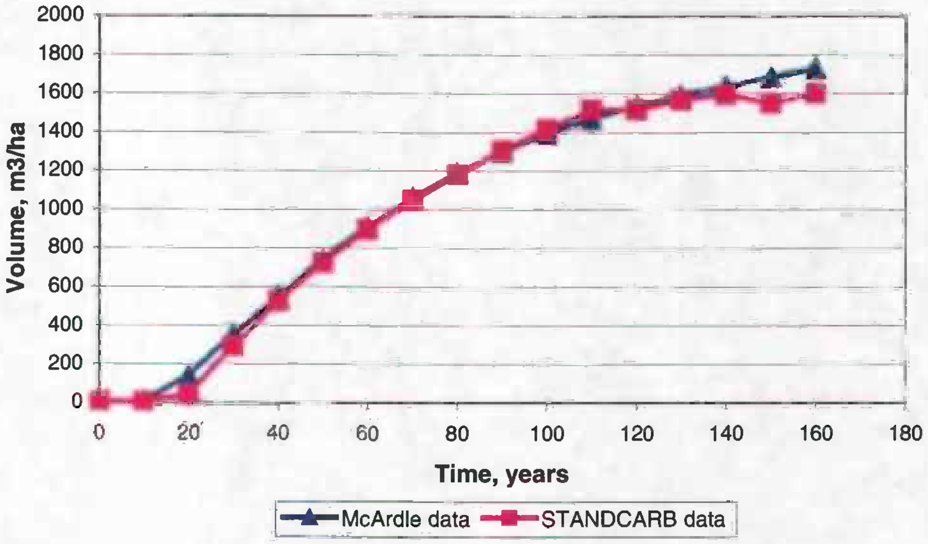
By looking at the change in SEV for a change in C we can tell how much should be paid to forest managers for employing the forest management regime that results in greater storage of C.

4 RESULTS

4.1 STANDCARB calibration for volume growth over time

For each site index, the growth curve constructed from STANDCARB data was fit to the growth curve constructed from McArdle growth data for given species. Site Index values were increased in STANDCARB for Douglas fir and Western Hemlock in order to make STANDCARB curves fit better with real data for these species. The example for site index 1High is shown in Figure 4.1. Figure 4.1 shows that adjusted STANDCARB growth curve has a good fit to McArdle data.

Figure 4.1. Growth curve from STANDCARB in comparison to growth curve from McArdle real data.



4.2 Model calibration for carbon pools

The original comparison of STANDCARB C pools data to Oregon Cascades data (Smithwick et al., Submitted) showed higher balances for STANDCARB branch and dead pools. The parameter values were adjusted for Douglas fir and Western hemlock in Growth.prm and Decomp.prm files. The following adjustments were made in STANDCARB parameter files.

The adjustments were made in Mort.prm file. MaxAge was changed to 1200 and TimeClose was changed to 120 for Douglas fir. Therefore, MaxDensity in Simul.dvr was adjusted from values obtained from runs for TimeClose 100 to values calculated for TimeClose 120. This change increased number of PSME upper trees in year 500 from 6 to 23. The volume for PSME/TSHE was 1/6 (103/672), and after increase in MaxAge it became 1/1 (430/479) at year 500.

Bole - Branch ratio was changed for PSME from 0.250 to 0.110, and for TSHE from 0.850 to 0.340 in Growth.prm file. This change decreased branch C from 100 to 43.1. Compare to Andrews Live branch C of 38, it became closer. The percent of Live branch from Live C is now 6.8 for Andrew's and 8.1 for StandCarb. Another parameter adjusted in Growth.prm file was Coarse Root – bole ratio for PSME from 0.770 to 0.620 and for TSHE from 0.650 to 0.520. This change decreased coarse root C.

Percent of snags was increased from 44 to 60 in EcoRegion.prm file. The result was increase in number of snags and decrease in number of logs.

Decay rates were adjusted in DecayPool.prm file for stable soil from 0.01 to 0.012 (went down from 196 to 121), for stable wood from 0.05 to 0.2 (from 74 to 11), and for stable foliage from 0.05 to 0.2 (from 46 to 11.8).

Several decay rates were adjusted in Decomp.prm file. Decay rates were increased for dead coarse roots and branches for PSME and TSHE from 0.1 to 0.15 (multiplying by 1.5). Another change in Decomp.prm file was made to sapwood and heartwood decay rates. They were increased for PSME from 0.05 to 0.07 for sapwood and from 0.015 to 0.02 for heartwood. The changes for TSHE were 0.05 to 0.07 for sapwood and 0.05 to 0.07 for heartwood.

Snag Fall Optimum Lag was increased from 20 to 30 for PSME, and from 10 to 20 for TSHE. This change decreased the logs C pool and increased snag C pool. The log to snag percent ratio in STANDCARB (55.6/44.4) became closer to Andrew's data (54.6/45.4).

Average C values were compared by dead and live C pools. The percent value from the total C was calculated for each pool. The results are presented in Table 4.1 and Table 4.2.

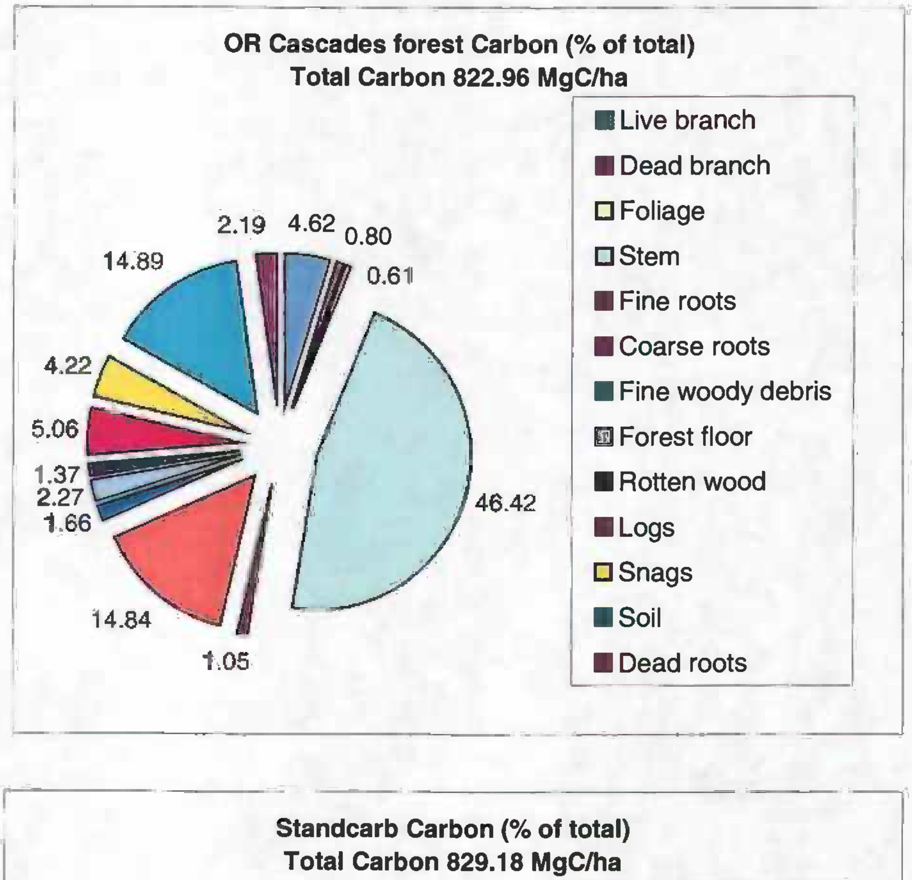
Table 4.1. Live C pools.

	Units	Live branch	Dead branch	Foliage	Stem	Fine Roots	Coarse roots
OR Cascades	Ave	38.0	6.6	5.0	382.0	8.6	122.2
	%	4.62	0.8	0.61	46.42	1.05	14.84
STANDCARB	Ave	43.1	-	8.7	353.8	5.9	117.3
	%	5.2	-	1.05	42.67	0.71	14.15

Table 4.2. Dead C pools and soil.

	Units	Fine woody debris	Forest floor	Rotten Wood	Logs	Snags	Soil	Dead Roots
OR Cascades	Ave	13.7	18.7	11.3	41.7	34.7	122.53	18.0
	%	1.66	2.27	1.37	5.06	4.22	14.89	2.19
STANDCARB	Ave	12.9	23.9	11.3	54.8	43.7	121.4	32.4
	%	1.55	2.89	1.36	6.61	5.28	14.65	3.9

Figure 4.2. C pool values from Oregon Cascades forest and STANDCARB model.

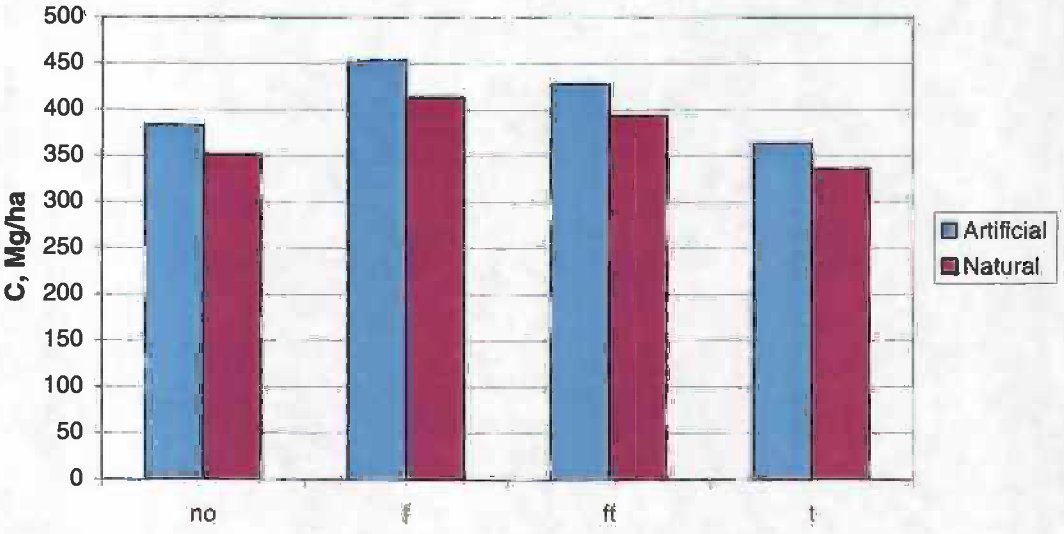


The total average C stored by Oregon Cascades old-growth forest was calculated to be 822.96 MgC/ha (Smithwick et al., Submitted). The average total C produced by STANDCARB model for similar conditions was 829.18 MgC/ha. The difference between these values was 0.8 percent. The percent of total C stored by various C pools is illustrated in Figure 4.2 for Oregon Cascades forest data compared to STANDCARB output data.

4.3 Carbon sequestration results

The results of STANDCARB runs for the 50 regimes used in this analysis showed that for artificial regeneration average annual C varied from 363.87 MgC/ha (with 50-year rotation with thinning) to 826.36 MgC/ha (with 150-year rotation with GE).

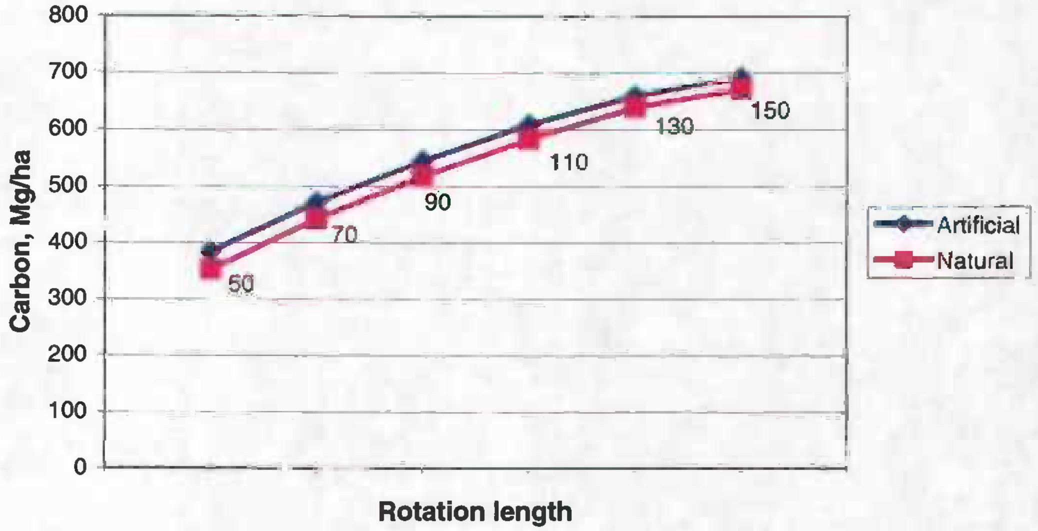
Figure 4.3. Average C in Mg/ha for 50-year rotation with artificial and natural regenerations, where no – no treatment, f – GE, ft – GE and thinning, t – thinning



For natural regeneration average annual C varied from 335.99 MgC/ha (with 50-year rotation with thinning) to 802.73 MgC/ha (with 150-year rotation with GE). The use of artificial regeneration compared to natural gave a 20-30 MgC/ha increase for all regimes (Figure 4.3). The treatment with GE gave the highest average C for every rotation. The treatment with just thinning gave the lowest average C for every rotation.

Average C storage increased with longer rotations. Figure 4.4 gives an example for clearcut of 50 to 150-year rotations with no treatment applied.

Figure 4.4. Average C for clearcut of 50 to 150-year rotations with no treatment applied.



The average C for group-selection regime was equal to 543.94 MgC/ha and for single-tree selection regime it was equal to 489.08 MgC/ha.

4.4 Timber havest results

Western hemlock comprised only 0-2 % of total harvest for clearcutting regimes. Therefore, Western hemlock was ignored in the calculation of total harvest and SEV for clearcutting regimes.

The total average harvest over rotation periods for artificially regenerated Douglas fir (thinning + clearcutting) varied from 505.34 m^3/ha (with 50-year rotation no treatment) to 1782.24 m^3/ha (with 150-year rotation with GE and thinning). The total annual harvest for naturally regenerated Douglas fir (thinning + clearcutting) varied from 463.19 m3/ha (with 50-year rotation no treatment) to 1730.97 m3/ha (with 150-year rotation with GE and thinning). The use of artificial regeneration compared to natural regeneration gave a 20-50 m3/ha increase in harvest for all regimes. The timber volumes harvested by each regime are presented in Appendix B.

For the group-tree selection regime, Western hemlock did not become a significant part of timber harvest until the end of regulation period. At that time, every harvested tree group at age 90 was about one quarter Western hemlock by timber volume. This maybe due to Douglas fir being a less shade tolerant species than Western Hemlock, when in smaller openings Western Hemlock replaced part of Douglas fir trees. Therefore, Western hemlock was included into calculation of total harvest and SEV. On average every 30 years when one third of the stand was harvested at age 90, the harvested timber volume included 138.4 m3/ha of Douglas fir and 47.9 m3/ha of Western Hemlock.

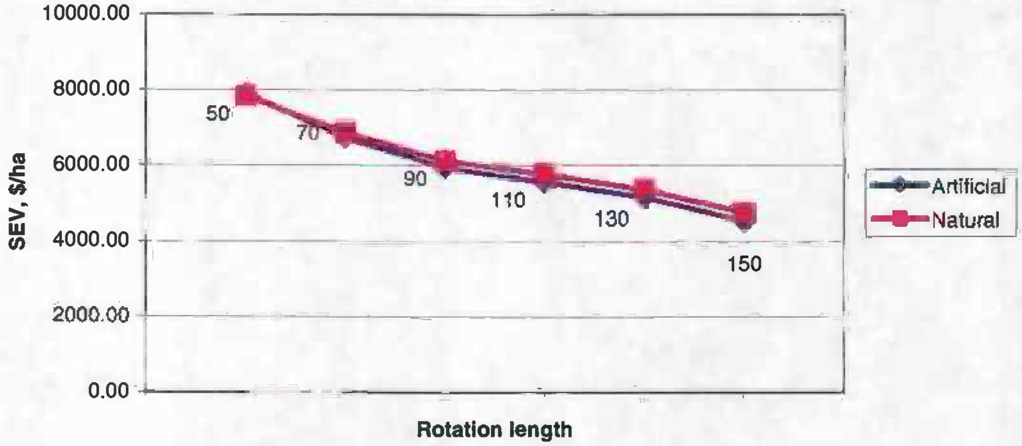
Similarly to group-tree selection, the Western hemlock did not become a significant part of timber harvest until the end of regulation period for single-tree selection harvest. On average every 20 years when one fifth of the stand was harvested at age 100, the harvested timber volume included 33.4 m3/ha of Douglas fir and 137.36 m3/ha of Western Hemlock.

4.5 SEV results

The results of our analysis suggested that SEV was highest with short rotations and natural regeneration (Figure 4.5). SEV decreased with longer rotation age, even becoming negative for the regime with 150-year rotation with artificial regeneration. SEV for treatments with natural regeneration was higher compared to same treatments with artificial regeneration for every treatment used in the analysis except 50-year rotation with artificial regeneration, GE and thinning (50art_ft). The SEV difference between artificial and natural regeneration treatments widened with rotation length.

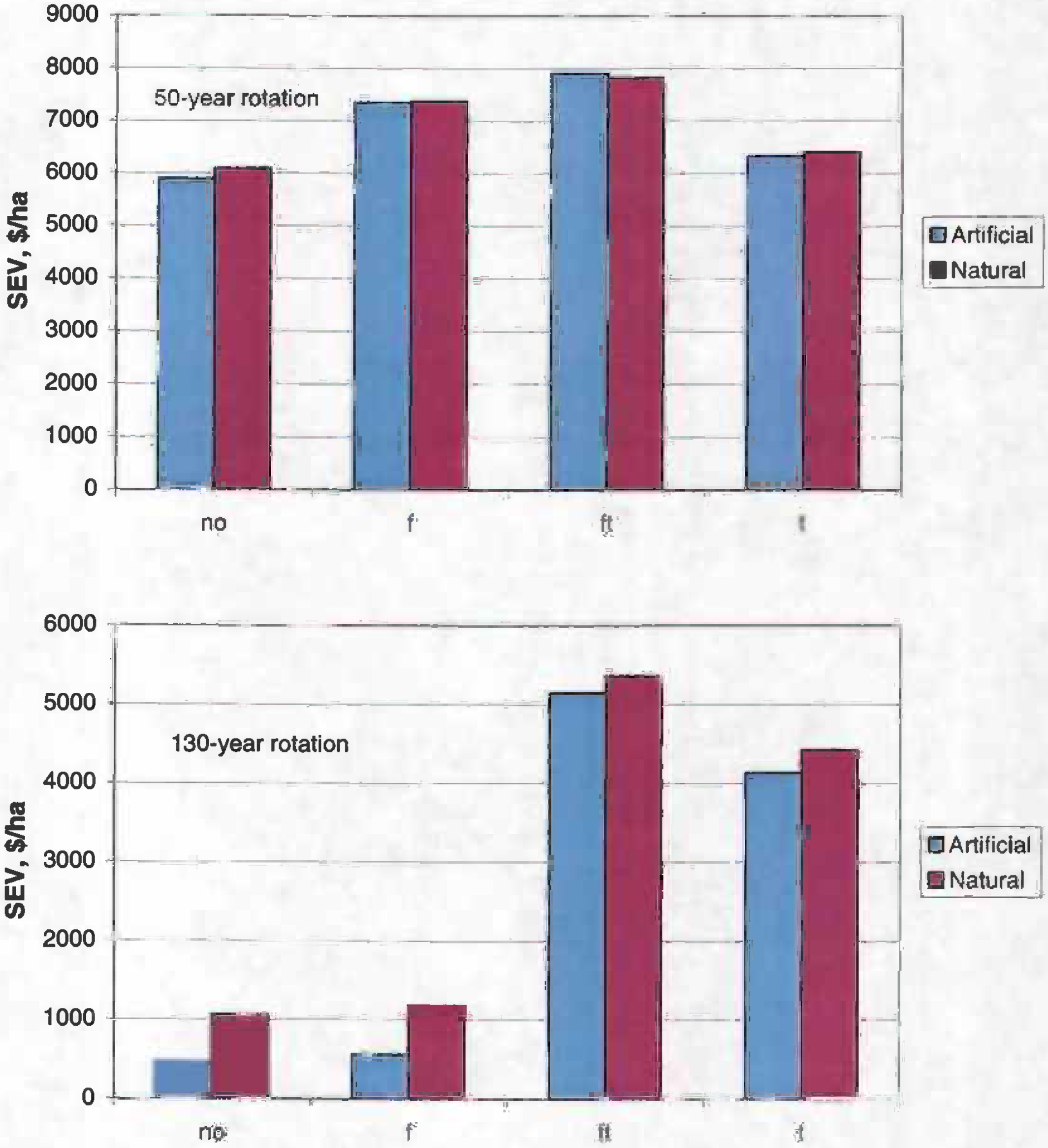
The maximum SEV was $7904.30 per hectare ($/ha) using a 50-year rotation with artificial regeneration, GE and thinning (50art_ft). The maximum SEV for regimes without GE was $6406.84/ha using a 50-year rotation with natural regeneration and thinning (50nat_t). For the group-tree selection regime, SEV was equal to $560.55/ha. The single-tree selection regime had SEV equal to $2171.99/ha.

Figure 4.5. SEV in relation to rotation length.



Looking at changes in SEV for different treatments with same rotation length (Figure 4.6), we can see that SEV is higher for treatments with GE than without GE.

Figure 4.6. SEV with different treatments for a single rotation length.



Thinning provides timber and cash flow in the beginning of the rotation. The difference in SEV for regimes with thinning compared to no thinning regimes became greater as rotations increased. For the 50-year rotation this difference between regimes with thinning and regimes without thinning was about $400-600/ha. For the 130-year rotation the difference increased to about $4000/ha.

4.6 DEA results

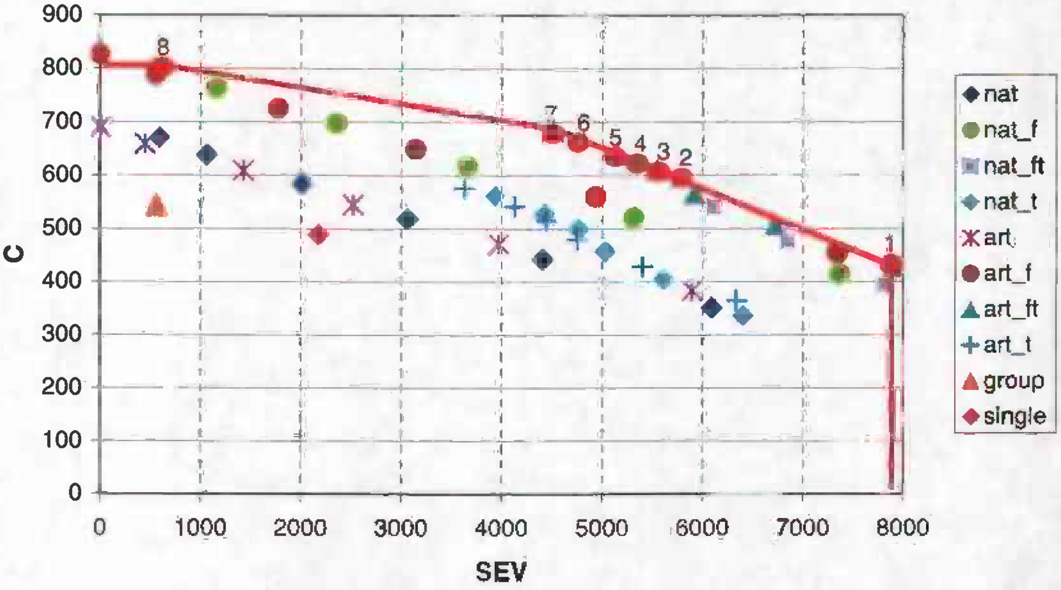
The total of 48 observations were used in Data Envelopment Analysis. Two observations had negative SEV, and were not included into DEA analysis (150a and 150af). For each regime, inputs were constant and the two output values were average C and SEV. Using the Farrell Output-Oriented Measure of Technical Efficiency, Fo(x,y), we found 8 efficient regimes (Appendix C). The efficiency score for other regimes varied from 1.01 to 1.48 for the regime with single-tree selection (single).

The locus of efficient regimes is connected with red line in Figure 4.7. This line is the simulated production possibility frontier under the assumption that convex combinations of adjacent efficient regimes are also feasible.

The eight efficient regimes included (Figure 4.7):

- 50-year rotation with –aft - artificial regeneration, GE and thinning (point 1);
- 110-year rotation with – nft - natural regeneration, GE and thinning (point 2);
- 110-year rotation with aft (point 3);
- 130-year rotation with nft (point 4);
- 130-year rotation with aft (point 5);
- 150-year rotation with nft (point 6);
- 150-year rotation with aft (point 7);
- 150-year rotation with natural regeneration and GE (point 8).

Figure 4.7. Best practice frontier for 48 observation points.



Most of the efficient regimes involved the intensive silviculture with artificial regeneration, GE and thinning. There were 6 different rotations with this most intensive regime, and four of them were selected by DEA as efficient. Two rotation ages of 70 and 90 were not selected as efficient, but DEA analysis showed that they were very close to being efficient since their efficiency scores were 1.01 and 1.02.

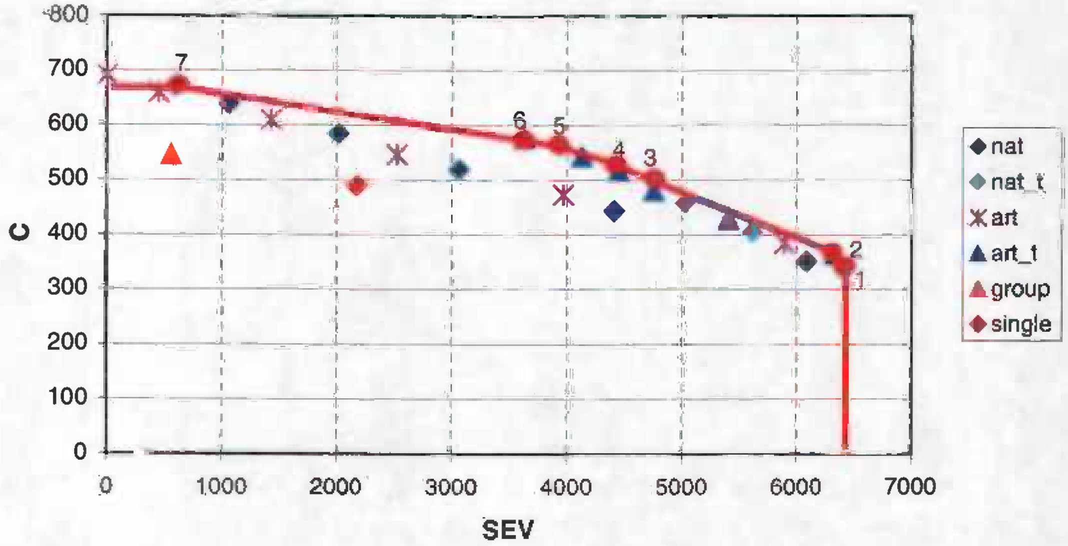
If regimes with GE were excluded from the DEA analysis, we received very similar results with similar points being selected as efficient (Appendix B).

With the set of 25 regimes the Farrell Output-Oriented Measure of Technical Efficiency, Fo(x,y) selected 7 regimes that had efficiency score of 1.00 (Figure 4.8):

- 50-year rotation with natural regeneration and thinning (point 1);
- 50-year rotation with artificial regeneration and thinning (point 2);
- 110-year rotation with natural regeneration and thinning (point 3);

- 130-year rotation with natural regeneration and thinning (point 4);
- 150-year rotation with natural regeneration and thinning (point 5);
- 150-year rotation with artificial regeneration and thinning (point 6);
- 150-year rotation with natural regeneration (point 7).

Figure 4.8. Production efficiency frontier for regimes with no GE.



4.7 Marginal cost calculation

We calculated marginal costs of increasing C storage by moving along the production possibility frontier. The marginal cost for 8 efficient regimes selected from the set of 48 observations is presented in Table 4.3. This marginal cost varied from \$10.34/MgC in moving from point 2 to point 3 in Figure 4.7 to \$32.79/MgC for a change from point 7 to point 8.

Table 4.3. Marginal cost for 8 efficient regimes.

Point	Treatment	C, Mg/ha	SEV, $/ha	MC, $/MgC
1	50aft	428.29	7904.30	
				13.28
2	110nft	589.55	5763.15	
				10.34
3	110aft	610.06	5550.98	
				14.67
4	130nft	623.28	5357.02	
				12.61
5	130aft	640.17	5143.96	
				14.42
6	150nft	667.48	4750.02	
				15.14
7	150aft	682.96	4515.72	
				32.79
8	150nf	802.73	588.76	

If only the seven efficient points without GE were considered, then calculated marginal cost varied from $2.66/MgC moving from point 1 to point 2 in Figure 4.8 to $32/MgC moving from point 6 to point 7 (Table 4.4).

Table 4.4. Marginal cost for 7 efficient regimes without GE.

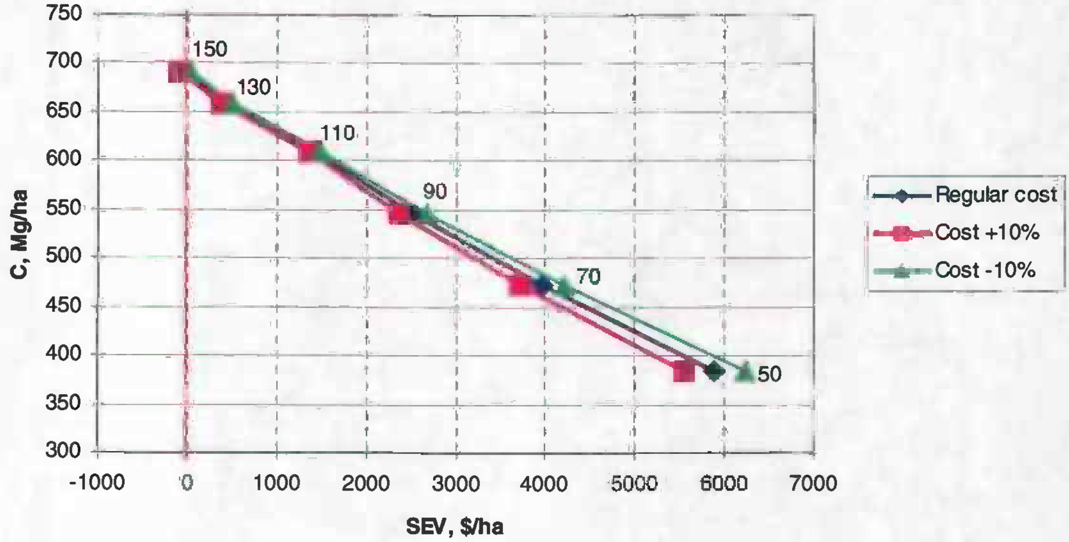
Point	Treatment	C, Mg/ha	SEV, $/ha	MC, $/MgC
1	50nt	335.99	6406.84	
				2.66
2	50at	363.87	6332.68	
				11.61
3	110nt	498.44	4770.70	
				11.97
4	130nt	527.06	4428.24	
				14.18
5	150nt	561.47	3940.36	
				21.61
6	150at	575.78	3631.07	
				32.00
7	150n	670.78	591.48	

As Tables 4.3 and 4.4 show, marginal costs generally increased as we moved from regimes favoring high SEV and relatively low C to those with low SEV and high C. A comparison of Table 4.3 to Table 4.4 also reveals that marginal cost calculations were, with one exception, insensitive to the exclusion of the GE treatment. The exception is the calculated $2.66 in Table 4.4.

4.8 Sensitivity analysis

We subjected our results to sensitivity analysis with regard to two sets of assumptions made in calculating SEV. First we analyzed the effect of increase and decrease in treatment costs by 10 percent.

Figure 4.9. SEV with change in treatment costs for artificial regeneration with no treatment.



There was a negative correlation between SEV and treatment cost. The difference in SEV with change in treatment costs was greater for shorter rotations, because their silvicultural treatments had a greater value with discounting than treatments applied further in time (Figure 4.9).

With the 10 percent decrease in costs, SEV became higher for all rotations resulting in all SEV values being positive, and all 50 regimes included into DEA analysis. Only 5 regimes were selected as being efficient from which 4 were the same as base cost scenario. All selected regimes included artificial regeneration with 4 regimes having the most intensive silviculture with artificial regeneration, GE and thinning. The marginal cost for these 5 efficient regimes varied from $13.65/MgC to $33.84/MgC (Table 4.5).

Table 4.5. Marginal cost for 5 efficient regimes with 10 percent decrease in costs.

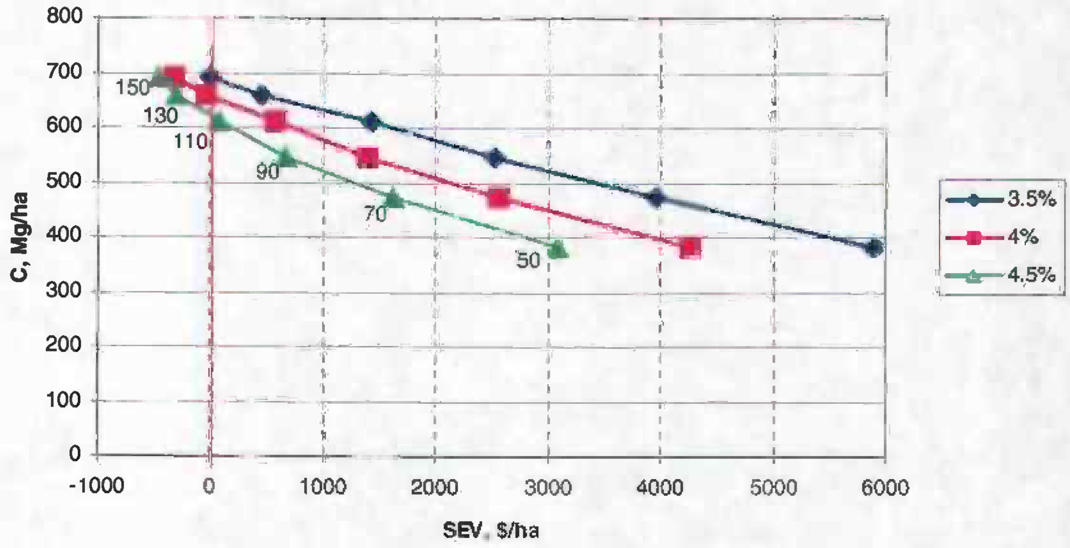
Point	Treatment	C, Mg/ha	SEV, $/ha	MC, $/MgC
1	50aft	428.29	8419.42	13.65
2	110aft	610.06	5938.61	13.62
3	130aft	640.17	5528.61	14.58
4	150aft	682.96	4904.74	33.84
5	150af	826.36	51.89	

With the increase in costs by 10 percent, there were 8 efficient points among which 7 were the same as base cost scenario. Two points had a 50-year rotation, and marginal cost while moving from point with natural regeneration to point with artificial regeneration was $1.26/MgC (Table 4.6). All cost scenarios had 3 common regimes, which included 50aft, 110aft and 150aft.

Table 4.6. Marginal cost for 8 efficient regimes with 10 percent increase in costs.

Point	Treatment	C, Mg/ha	SEV, $/ha	MC, $/MgC
1	50nft	393.58	7432.81	
				1.26
2	50aft	428.29	7389.17	
				11.90
3	110nft	589.55	5469.55	
				14.93
4	110aft	610.06	5163.35	
				7.42
5	130nft	623.28	5065.22	
				13.87
6	150nft	667.48	4452.04	
				21.02
7	150aft	682.96	4126.7	
				29.68
8	150nf	802.73	571.43	

Figure 4.10. SEV with change in discount rate for the regime with artificial regeneration and no treatment.



SEV also had a negative correlation with real discount rate. With the increase in discount rate, SEV decreased. The effect of discount rate on SEV for the regime with artificial regeneration is shown in Figure 4.10. We varied the discount rate from 3.5 to 4.5 percent. The increase in discount rate resulted in more SEV values becoming negative. There were 4 negative SEV values with 4 percent discount rate, and 5 negative SEV values with 4.5 percent discount rate resulting in smaller number of regimes subjected to DEA.

Five regimes were selected as efficient from the set of 46 regimes with the increase of real discount rate to 4 percent (Table 4.7). Marginal cost varied from \$2.03/MgC while moving from point 1 to point 2 to \$24.03/MgC while moving from point 4 to point 5.

Table 4.7. Marginal cost for 5 efficient regimes with 4 percent real discount rate.

Point	Treatment	C, Mg/ha	SEV, \$/ha	MC, \$/MgC
1	50nft	393.58	5927.73	2.03
2	50aft	428.29	5857.36	10.31
3	150nft	667.48	3390.83	19.67
4	150aft	682.96	3086.29	24.03
5	150nf	802.73	208.52	

With the increase of real discount rate to 4.5 percent, only 4 regimes were selected as efficient from the set of 45 regimes (Table 4.8). Marginal cost for these regimes varied from \$5.23/MgC while moving from point 1 to point 2 to \$18.17/MgC while moving from point 3 to point 4.

Table 4.8. Marginal cost for 4 efficient regimes with 4.5 percent real discount rate

Point	Treatment	C, Mg/ha	SEV, $/ha	MC, $/MgC
1	50nft	393.58	4545.41	
				5.23
2	50aft	428.29	4364.01	
				7.86
3	150nft	667.48	2482.88	
				18.17
4	150nf	802.73	25.39	

All discount rate scenarios had 3 common regimes, which included 50aft, 150nf and 150nft.

Overall, one regime with 50-year rotation, artificial regeneration, GE, and thinning was selected in all 5 scenarios of sensitivity analysis. Three regimes were selected in 4 scenarios, and in 5th scenario their efficiency score was equal to 1.01 that barely misses the production possibility frontier line. These regimes included 150aft, 150nf and 150nft.

With the change in costs and discount rate, marginal cost was close to its range with the base scenario of 3.5 percent discount rate. The exception was the case when two of the 50-year rotation regimes were selected as efficient in the same scenario. While moving from one 50-year regime to another, the marginal cost was very low: $1.26/MgC (with 10 percent increase in costs), $2.03/MgC (with 4% discount rate), and $5.23/MgC (with 4.5% discount rate).

5 CONCLUSION

We analyzed 50 forest management regimes using the STANDCARB model to simulate Pacific Northwest forest production of C and timber. These regimes included 48 regimes with clearcutting rotations varying from 50 to 150 years, and two partial cutting regimes of group and single-tree selection.

The STANDCARB model is a unique C simulation model designed for the Pacific Northwest forests. This model helps to examine the effects of silvicultural treatments on the dynamics of living, detrital, and forest products C pools of forest stands. Simulation experiments included 5 replicates of each treatment. They were used to study the effects of rotation length, tree utilization level, and site preparation on total and forest products C stores.

Our simulations indicated that total average C stored by the forest is affected by forest management regime applied. The greater C stores were achieved by lengthening clearcut rotations. In our analysis the C store increased from 428.29 MgC/ha for a 50-year rotation with artificial regeneration, GE and thinning to 682.96 MgC/ha with 150-year rotation with the same treatments. The increase in C store achieved by lengthening the rotation from 50 to 150 years was 1.6-1.8 times. The maximum amount of C among regimes included into analysis was achieved by implementing 150-year rotation with artificial regeneration and GE with average C store of 826.36 MgC/ha, however this regime had negative SEV.

The use of artificial regeneration compared to natural gave a 15-30 MgC/ha increase for all regimes. Thinning decreased C store by about 20 MgC/ha with 50-year rotation, and by up to 140 MgC/ha with 150-year rotation.

Lengthening of rotation age also affected harvested timber volumes. The total harvest obtained from thinning plus clearcutting for 50-year rotation with artificial regeneration, GE and thinning was 653.69 m3/ha, while timber harvest for 150-year rotation with artificial regeneration, GE and thinning was 1782.24 m3/ha.

Soil expectation value (SEV) was used as a measure of economic value of different silvicultural regimes. It was calculated using a 3.5% real discount rate. SEV had a negative relationship with the length of rotation age decreasing from $7904.3/ha for 50-year year rotation with artificial regeneration, GE and thinning to $4515.72/ha for 150-year rotation with artificial regeneration, GE and thinning. SEV reached negative values for two regimes with 150-year rotation, artificial regeneration and artificial regeneration and no thinning. This can be explained by the fact that revenue for these regimes is obtained at the end of the rotation, with no intermediate revenues from thinning.

The economic value of silvicultural regimes calculated in this project did not include such costs as road construction and release. Also, it did not consider taxes, and discount rate in the market might be higher. Therefore, the market values of bare forest land in Oregon would be lower depending on type and size of owner, compared to values calculated in this project.

The set of efficient silvicultural regimes was determined using Data Envelopment Analysis (OnFront software). Out of 48 regimes analyzed, the DEA selected the following eight efficient regimes:

- 50-year rotation with artificial regeneration, GE and thinning (50aft);
- 110-year rotation with natural regeneration, GE and thinning (110nft);
- 110-year rotation with artificial regeneration, GE and thinning (110aft);
- 130-year rotation with natural regeneration, GE and thinning (130nft);
- 130-year rotation with artificial regeneration, GE and thinning (130aft);
- 150-year rotation with natural regeneration, GE and thinning (150nft);
- 150-year rotation with artificial regeneration, GE and thinning (150aft);
- 150-year rotation with natural regeneration and GE (150nf).

The marginal cost generally increased for regimes with higher C stores or longer rotations. Moving from a 50-year rotation with artificial regeneration, GE and thinning, the typical regime for private industrial forests, to longer rotation of 110 with natural regeneration, GE and thinning, the marginal cost was calculated to be $13.28/MgC. In this case, C store increased from 428.29 MgC/ha to 589.55 MgC/ha. In contrast, going from 150-year rotation with artificial regeneration, GE and thinning to a 150-year rotation with natural regeneration and GE, marginal cost was $32.79/MgC. The change in C store associated with this was from 682.96 MgC to 802.73 MgC.

The DEA was also applied to the set of regimes without GE because the GE function in STANDCARB was modeled by the use of higher Site Index. The results of DEA showed that slope of the production frontier for regimes with no GE is similar to regimes with GE.

With emission trading being adopted as part of the market-based approach by parties to the United Nations Framework Convention on Climate Change at the Kyoto conference, the economic values of carbon sequestration with different forest management regimes calculated in this project can be used as an estimate of cost per ton of carbon.

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APPENDICES

Appendix A. STANDCARB parameter and driver files.

STANDCARB parameter and driver files used with 50-year rotation regime with artificial regeneration.

```
----------------------------------------------------------------------
File:  Simul.dvr
----------------------------------------------------------------------
Program    StandCarb
Data_File  Simulation_Parms
Version    1


SpeciesUpper        psme
SpeciesLower        tshe

SiteName            testsite1

GrowthMethod        Siteindex
SiteIndexSpecies    psme
SiteIndex           Site3Medium

Regen               af
MaxTreeDensity      560000
MaxTreeCells        100

#ofRows             10
#ofCols             10

#ofReps              5
TimeEnd            1000
Interval             5

CellWidth           15

TimeHerb             1
TimeShrub            5
TimeUpper            5
TimeLower           15

Border             same

NeighborOnOff        1
Cohort               1
Restart              1

PET_Reduction       10
InitialSoilCarbon  304
Units                C

GPP_DecreaseMax      0
GPP_Shape            1
```

```
DiagnosticsMode      10
PlantDiag             0
DieOutDiag            0
ReplacementDiag       1
DensityDiag           1
InterceptionDiag      0
WaterBalanceDiag      0
TranspirationDiag     0
TempResponseDiag      0
DetritalMoistureDiag 0
AbioticResponseDiag  0
LightDiag             0
RespirationDiag       0
MortalityDiag         0
SubstrateQualityDiag 0
WaterPotRespDiag      0
SpeciesDiag           0
NeighborDiag          0
YearNeighbor        100

RandomNumSeed      -67860
```

File: Locate.dvr

```
Locate driver file for StandCarb

Model   File   Site         Soil
Slope   Soil            Drainage
#       #      Name         Texture  Ecoregion Long   Lat   Elev   Aspect
Steep   Depth   Rocks   Factor

ML02    22     default        loam    OTHR       123    40     300    180
0      100      5     100
ML02    22     testsite1      loam    Other      123    44     100    180
20      100      5     100
ML02    22     testsite2      loam    ORCW       123    44    1000    180
0      100      5      50
ML02    22     testsite3      loam    ORCW       123    44    3000    180
0      100      5      50
```

File: Climate.dvr

```
Climate driver file - StandCarb

Model   File          Temp____________
#       #      Month  Min      Max     24-hr   Precip

ML02    23     Jan    -1.5      3.20    0.30    39.0
ML02    23     Feb    -0.20     7.00    2.70    27.0
ML02    23     Mar     0.10     9.40    3.80    27.0
ML02    23     Apr     1.70    14.60    7.40    14.0
```

```
ML02   23    May     4.40  19.30  11.70    11.0
ML02   23    Jun     7.30  23.30  14.90     6.0
ML02   23    Jul     9.00  28.70  18.30     1.0
ML02   23    Aug     8.60  28.00  17.40     4.0
ML02   23    Sep     6.30  24.10  13.50     8.0
ML02   23    Oct     3.40  15.80   8.10    18.0
ML02   23    Nov     0.70   7.50   3.50    34.0
ML02   23    Dec    -0.90   3.6    1.10    41.0
```

File: Radiate.dvr

```
Radiation driver file - StandCarb

                                             Sunrise   Solar
Model  File        Solar Radiation________  Azimuth   Alt-Angle
#      #     Month  Diffuse  Direct   Total  Angle     South

ML02   24     Jan     92.78   51.11  143.90    71.30    29.08
ML02   24     Feb    125.47   83.93  209.39    78.88    37.04
ML02   24     Mar    167.30  118.54  285.84    87.98    47.58
ML02   24     Apr    207.88  180.51  388.39    98.01    59.42
ML02   24     May    233.74  234.26  468.00   106.60    68.79
ML02   24     Jun    231.63  308.88  540.50   110.97    73.09
ML02   24     Jul    145.10  552.26  697.36   108.99    71.18
ML02   24     Aug    191.46  310.35  501.81   101.59    63.46
ML02   24     Sep    174.19  189.08  363.26    91.87    52.22
ML02   24     Oct    136.80  104.75  241.54    81.85    40.40
ML02   24     Nov    100.48   59.15  159.63    73.30    31.09
ML02   24     Dec     83.78   44.42  128.20    69.09    26.95
ML02   24    Year    157.55  186.44  343.99    97.03    57.89
```

File: HarvInt.dvr

```
Harvest Interval driver file - StandCarb

             Pre-Commercial__________ Commercial_____________ Clear-
Cut______________            Herbicide_____________
Model  File  Interval___        Fire  Interval___       Fire
Interval___        Fire  Salvage_  UTree_____  LTree_____
#      #     UTree LTree  Util  Type  UTree LTree  Util  Type  UTree
LTree  Util  Type  Int Util  Int Effect  Int Effect

ML02   26      0     0    1     0       0     0    3     0    300
300    3     0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0    350
350    3     0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0    400
400    3     0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0    450
450    3     0      0   2      0   1      0   3
```

```
ML02   26      0     0    1     0       0     0    3     0     500
500    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     550
550    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     600
600    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     650
650    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     700
700    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     750
750    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     800
800    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     850
850    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     900
900    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0     950
950    3    0      0   2      0   1      0   3
ML02   26      0     0    1     0       0     0    3     0    1000
1000    3    0      0   2      0   1      0   3
```

File: CutPatt.dvr

```
Cut Pattern driver file for StandCarb

ML02  27
Year  300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850,
900, 950, 1000
Species all
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
downhill
```

File: WFPatt.dvr

```
Wildfire pattern driver file - StandCarb

ML12  28
Year 1500
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
```

```
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1
downhill
```

File: WFireInt.dvr

```
WildFire Interval driver file - StandCarb

Model   File   Lite  Med   Hot
#       #      Fire  Fire  Fire

ML02    25       0     0     0
```

File: Estab.prm

```
Establishment probabilities for layers - StandCarb model

                   Natural_____________________
Artifical___________________
Model File         Fast________   Slow_________   Fast_________
Slow_________
#     #     Layer  Open   Closed  Open   Closed  Open   Closed  Open
Closed

ML02    1   Herb   0.500  0.250   0.600  0.300   0.600  0.300   0.600
0.300
ML02    1   Shrub  0.300  0.150   0.300  0.150   0.300  0.150   0.300
0.150
ML02    1   Tree   0.200  0.050   0.030  0.050   0.600  0.050   0.100
0.050
```

File: TreeReg.prm

```
Program     StandCarb
Data_File   Tree_Regeneration_Parms
Version     1

>           Light____     DegreeDays    WaterPot
> Species   Max    Min    Max     Min   Max  Min    Sprout

  Abam      0.80  0.05    3095    625   2.0  0.10     0
  Abco      0.95  0.10    2640    990   2.5  0.10     0
  Abgr      0.90  0.10    2640    990   2.0  0.10     0
```

```
Abla     1.00  0.10   1200   350   1.8  0.10    0
Abpr     1.00  0.50   1854   885   2.0  0.10    0
Abma     1.00  0.50   1854   885   2.0  0.10    0
Acma     1.00  0.25   2810   920   1.0  0.05    9
Alru     1.00  0.90   3370   810   1.0  0.05    5
Arme     1.00  0.75   3095   625   2.5  0.10    9
Cach     1.00  0.75   3095   625   2.5  0.10    9
Cade     1.00  0.75   3500   900   2.5  0.10    0
Lide     0.90  0.25   3500   900   2.5  0.10    9
Pico     1.00  0.90   2000   350   2.5  0.05    0
Pila     1.00  0.75   3500   900   2.0  0.10    0
Pimo     1.00  0.75   3500   900   2.0  0.10    0
Pipo     1.00  0.90   3000   400   2.7  0.20    0
Pien     1.00  0.25   1500   350   1.7  0.05    0
Pisi     1.00  0.50   2000   400   1.5  0.05    0
Potr     1.00  0.90   3500   900   1.0  0.05    9
Prem     1.00  0.90   3500   600   2.0  0.10    9
Psme     1.00  0.50   3095   625   2.0  0.20    0
Quga     0.90  0.50   2880   975   2.5  0.20    9
Sese     1.00  0.25   2500   600   1.5  0.10    9
Thpl     0.80  0.25   3095   625   1.5  0.05    0
Tshe     0.90  0.05   3095   625   1.7  0.10    0
Tsme     1.00  0.25   1475   555   1.7  0.10    0
```

File: Growth.prm

```
Growth parameters for species - StandCarb model version 2

                                 Foliage Fine           Rate
Coarse
                    Light______  Prod    Root           Heart  Branch
Root                                          Heart-Rot
Model File          Comp  Ext    Rate    Foliage  Sap   Wood   Bole
Bole   Temp____  Wood_______   Height_________      Rate
#     #     Species Point Coeff  Max     Ratio    Live  Form   Ratio
Ratio  Min  Max  Pcnt Density  Max Rate Shape  Lag  Form

ML02  3     Herb       5  0.23   2.00     0.75    0.00  0.000  0.000
0.000    0   37   0.0   0.45     0 0.015  1.0    0  0.000
ML02  3     Shrub     30  0.40   1.20     0.50    0.00  0.000  1.500
1.500    0   37   0.0   0.45     0 0.015  1.0    0  0.000
ML02  3     Abam      10  0.15   0.50     0.33    6.60  0.039  0.500
0.750    0   37  90.0   0.40    60 0.015  2.0   50  0.020
ML02  3     Abco      10  0.15   0.50     0.33    9.50  0.039  0.500
0.770    0   37  90.0   0.35    60 0.015  2.0   50  0.020
ML02  3     Abgr      10  0.15   0.50     0.33    6.70  0.039  0.500
0.770    0   37  90.0   0.35    60 0.015  2.0   50  0.020
ML02  3     Abla      10  0.15   0.50     0.33    5.70  0.039  0.900
1.200    0   37  90.0   0.31    60 0.015  2.0   50  0.020
ML02  3     Abpr      10  0.15   0.50     0.33    6.60  0.039  0.350
0.720    0   37  90.0   0.37    60 0.015  2.0   50  0.020
ML02  3     Abma      10  0.15   0.50     0.33    6.60  0.039  0.480
0.650    0   37  90.0   0.36    60 0.015  2.0   50  0.020
```

```
ML02  3     Acma       20  0.32   0.50      0.33   18.50  0.010  0.220
0.380    0   37  90.0   0.44    30 0.015  2.0   50  0.020
ML02  3     Alru       20  0.32   0.75      0.33   13.70  0.010  1.500
0.550    0   37  90.0   0.37    30 0.015  2.0   25  0.020
ML02  3     Arme       20  0.32   0.50      0.33   13.70  0.059  0.850
0.950    0   37  90.0   0.60    30 0.015  2.0  100  0.010
ML02  3     Cach       20  0.32   0.50      0.33   12.20  0.059  0.850
0.900    0   37  90.0   0.60    30 0.015  2.0  100  0.010
ML02  3     Cade       10  0.15   0.50      0.33    8.90  0.105  0.500
1.000    0   37  90.0   0.35    60 0.015  2.0  100  0.005
ML02  3     Lide       20  0.32   0.50      0.33   12.20  0.059  0.900
1.000    0   37  90.0   0.60    30 0.015  2.0   50  0.020
ML02  3     Pico       20  0.15   0.50      0.33    5.70  0.024  0.350
0.900    0   37  90.0   0.38    40 0.015  2.0  100  0.010
ML02  3     Pila       10  0.15   0.35      0.33    5.70  0.059  1.900
0.900    0   37  90.0   0.34    70 0.015  2.0  200  0.010
ML02  3     Pimo       10  0.15   0.35      0.33    6.60  0.059  1.900
0.900    0   37  90.0   0.35    60 0.015  2.0  200  0.010
ML02  3     Pipo       20  0.15   0.55      0.33    6.80  0.011  0.330
0.570    0   37  90.0   0.38    60 0.015  2.0  200  0.010
ML02  3     Pien       10  0.15   0.50      0.33    5.90  0.043  0.400
0.850    0   37  90.0   0.33    60 0.015  2.0  100  0.010
ML02  3     Pisi       10  0.15   0.50      0.33    7.30  0.039  0.350
0.800    0   37  90.0   0.37    90 0.015  2.0  100  0.010
ML02  3     Potr       20  0.32   0.75      0.33    9.60  0.059  0.500
0.500    0   37  90.0   0.31    45 0.015  2.0   50  0.025
ML02  3     Prem       20  0.32   0.50      0.33   16.40  0.059  0.500
0.500    0   37  90.0   0.47    20 0.015  2.0   50  0.020
ML02  3     Psme       10  0.15   0.85      0.33    7.40  0.059  0.110
0.620    0   37  90.0   0.45    90 0.015  2.0  100  0.010
ML02  3     Quga       20  0.32   0.50      0.33   30.00  0.059  0.950
1.250    0   37  90.0   0.60    30 0.015  2.0  100  0.010
ML02  3     Sese        5  0.15   0.50      0.33    7.90  0.102  0.250
0.770    0   37  90.0   0.38    99 0.015  2.0  200  0.010
ML02  3     Thpl       10  0.15   0.50      0.33    6.90  0.102  0.550
1.500    0   37  90.0   0.32    60 0.015  2.0  200  0.010
ML02  3     Tshe        5  0.15   0.60      0.33    8.80  0.022  0.340
0.520    0   37  90.0   0.42    85 0.015  2.0  100  0.020
ML02  3     Tsme       10  0.15   0.50      0.33    8.80  0.022  0.850
0.650    0   37  90.0   0.42    60 0.015  2.0  100  0.020
```

```
-----------------------------------------------------------------------
File:  GrowLayer.prm
-----------------------------------------------------------------------
Growth parameters for plant layers
StandCarb model, version 2

Initial  Canopy  Bole
Model  File         Foliage_____  FineRoot____  Sapwood_____
Branch______  CRoot_______  HeartRot____  Foliage  Inter   Growth
#       #     Layer  Q10    Resp10  Q10    Resp10  Q10    Resp10  Q10
Resp10  Q10    Resp10  Q10    Resp10  Mass     Min     Effic
```

```
ML02   4     Herb   2.000 0.500   2.000 0.500   2.000 0.000   2.000
0.000   2.000 0.000   2.000 0.000   0.01     0.006   0.00
ML02   4     Shrub  2.000 0.500   2.000 0.500   2.000 0.050   2.000
0.050   2.000 0.050   2.000 0.000   0.01     0.006   0.50
ML02   4     LTree  2.000 0.250   2.000 0.500   2.000 0.017   2.000
0.017   2.000 0.017   2.000 0.010   0.01     0.006   1.00
ML02   4     UTree  2.000 0.250   2.000 0.500   2.000 0.017   2.000
0.017   2.000 0.017   2.000 0.010   0.01     0.006   1.00
```

File: Mort.prm

```
Mortality parameters - StandCarb model version 2

                                 Coarse
                          Branch Root                Turnover-Rates
Model File         Mort   Prune  Prune  Time    Age              Fine
#     #    Species Max    Max    Max    Close   Max  Foliage  Root

ML02  5    Herb    0.000  0.000  0.000      0      0   1.000  0.500
ML02  5    Shrub   0.010  0.020  0.010      0      0   0.500  0.500
ML02  5    Abam    0.010  0.020  0.005    100    500   0.200  0.500
ML02  5    Abco    0.010  0.020  0.005    100    500   0.200  0.500
ML02  5    Abgr    0.007  0.020  0.005    100    500   0.200  0.500
ML02  5    Abla    0.007  0.020  0.005    100    200   0.200  0.500
ML02  5    Abpr    0.010  0.020  0.005    100    500   0.200  0.500
ML02  5    Abma    0.010  0.020  0.005    100    500   0.200  0.500
ML02  5    Acma    0.018  0.020  0.005    100    200   1.000  0.500
ML02  5    Alru    0.018  0.020  0.005     50    120   1.000  0.500
ML02  5    Arme    0.010  0.020  0.005     50    150   0.333  0.500
ML02  5    Cach    0.018  0.020  0.005     50    150   0.333  0.500
ML02  5    Cade    0.010  0.020  0.005    100    900   0.200  0.500
ML02  5    Lide    0.018  0.020  0.005     50    150   0.333  0.500
ML02  5    Pico    0.010  0.020  0.005    100    400   0.333  0.500
ML02  5    Pila    0.012  0.020  0.005    100    500   0.333  0.500
ML02  5    Pimo    0.012  0.020  0.005    100    500   0.333  0.500
ML02  5    Pipo    0.012  0.020  0.005    100    600   0.333  0.500
ML02  5    Pien    0.010  0.020  0.005    150    500   0.200  0.500
ML02  5    Pisi    0.010  0.020  0.005    100    600   0.250  0.500
ML02  5    Potr    0.018  0.020  0.005     75    150   1.000  0.500
ML02  5    Prem    0.020  0.020  0.005     25    100   1.000  0.500
ML02  5    Psme    0.011  0.020  0.005    120   1200   0.200  0.500
ML02  5    Quga    0.010  0.020  0.005    100    300   1.000  0.500
ML02  5    Sese    0.005  0.020  0.005    150   1500   0.200  0.500
ML02  5    Thpl    0.010  0.020  0.005    100   1000   0.200  0.500
ML02  5    Tshe    0.013  0.020  0.005    100    600   0.250  0.500
ML02  5    Tsme    0.010  0.020  0.005    100    600   0.200  0.500
```

File: EcoRegion.prm

```
Program    StandCarb
Data_File  EcoRegions
```

```
Version    1

>                  % Snags_______
>                  Open    Closed  Local
> EcoRegion        Canopy  Canopy  Abundances

  CA_CoastRange      90      30    CA_Coast
  CA_CascadesWest    90      50    all_others
  OR_CascadesWest    90      50    all_others
  OR_CascadesEast    90      80    all_others
  OR_CoastRange      90      30    all_others
  WA_CascadesWest    90      50    all_others
  WA_CascadesEast    90      80    all_others
  Other              90      60    Other


Local_Abundances   CA_Coast  all_others  Other

            Abam        10        10         -
            Abco         -         1         -
            Abgr         1         1         -
            Abla         -         1         -
            Abpr        10        10         -
            Acma         1         1         -
            Alru         -        10         -
            Arme         1         1         -
            Cach         5         5         -
            Cade         -         1         -
            Pila         -         1         -
            Pimo         1         1         -
            Pien         -         1         -
            Potr         2         2         -
            Prem         5         5         -
            Psme        50        10        90
            Quga         -         1         -
            Thpl        20         5         -
            Tshe        40        10         5
            Tsme         -        10         -
```

File: Decomp.prm

```
Decomposition parameters - StandCarb model

                     Decay-Rates______________________________
Optimum-Lag__________________
Model File                   Fine   Coarse Sap   Heart           Snag
        Stable-Pools_____
#     #     Species  Foliage Root   Root   Wood  Wood    Branch  Fall
  Salv  Wood Foliage Soil

ML02   6    Herb     0.500   0.500  0.000  0.000  0.000  0.000      0
     0     0     5     5
ML02   6    Shrub    0.250   0.250  0.100  0.050  0.000  0.100      0
```

```
      0     10      5      10
ML02    6     Abam      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
ML02    6     Abco      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
ML02    6     Abgr      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
ML02    6     Abla      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
ML02    6     Abpr      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
ML02    6     Abma      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
ML02    6     Acma      0.250    0.150   0.150   0.050   0.050   0.150         5
      2     20      5      10
ML02    6     Alru      0.250    0.150   0.150   0.050   0.050   0.150         5
      2     20      5      10
ML02    6     Arme      0.250    0.150   0.100   0.050   0.010   0.100        10
      5     20      5      10
ML02    6     Cach      0.250    0.150   0.100   0.050   0.010   0.100        10
      5     20      5      10
ML02    6     Cade      0.150    0.150   0.100   0.050   0.005   0.100        20
     20     20      5      10
ML02    6     Lide      0.250    0.150   0.100   0.050   0.010   0.100        10
      5     20      5      10
ML02    6     Pico      0.150    0.150   0.100   0.050   0.020   0.100        10
      5     20      5      10
ML02    6     Pila      0.150    0.150   0.100   0.050   0.020   0.100        20
     10     20      5      10
ML02    6     Pimo      0.150    0.150   0.100   0.050   0.020   0.100        20
     10     20      5      10
ML02    6     Pipo      0.150    0.150   0.100   0.050   0.020   0.100        10
      5     20      5      10
ML02    6     Pien      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
ML02    6     Pisi      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
ML02    6     Potr      0.250    0.150   0.100   0.050   0.050   0.100         5
      2     20      5      10
ML02    6     Prem      0.250    0.150   0.100   0.050   0.005   0.100         5
      2     20      5      10
ML02    6     Psme      0.150    0.150   0.150   0.070   0.020   0.150        30
     20     20      5      10
ML02    6     Quga      0.250    0.150   0.100   0.100   0.050   0.100        10
     10     20      5      10
ML02    6     Sese      0.150    0.150   0.100   0.050   0.005   0.100        30
     30     20      5      10
ML02    6     Thpl      0.150    0.150   0.100   0.050   0.005   0.100        30
     20     20      5      10
ML02    6     Tshe      0.150    0.150   0.150   0.070   0.070   0.150        20
      5     20      5      10
ML02    6     Tsme      0.150    0.150   0.100   0.050   0.050   0.100        10
      5     20      5      10
```

```
----------------------------------------------------------------------
File:  DecayPool.prm
----------------------------------------------------------------------
Parameters for dead and stable pools
Standcarb model, version 2
                                                                Stable
  Area   Moist
Model File                           Temp  Moist___   Transfer  Decay
  Mass   Store  Matric___  Diffuse__   Temp_____   Drying
#     #     Pool              Q10    Opt   Min  Max   Rate      Rate
  Ratio  Max    Shape Lag  Shape Lag   Shape Lag  Constant

ML02   7    DeadFoliage       2.000  45     30  350   0.300     0.0000
  20.00  300     5.0   0    15    4     15   4   0.00150
ML02   7    DeadFineRoot      2.000  45     30  400   0.300     0.0000
   0.00  300     5.0   0    15    4     15   4   0.00000
ML02   7    SalvSnagSapWood   2.000  45     30  150   0.150     0.0000
   0.02  300     5.0   0    15    4     15   4   0.00075
ML02   7    SalvSnagHeartWood 2.000  45     30  150   0.150     0.0000
   0.02  200     5.0   0    15    4     15   4   0.00025
ML02   7    SnagSapWood       2.000  45     30  150   0.150     0.0000
   0.02  300     5.0   0    15    4     15   4   0.00075
ML02   7    SnagHeartWood     2.000  45     30  150   0.150     0.0000
   0.02  200     5.0   0    15    4     15   4   0.00025
ML02   7    SalvLogSapWood    2.000  45     30  150   0.150     0.0000
   0.10  300     5.0   0    15    4     15   4   0.00075
ML02   7    SalvLogHeartWood  2.000  45     30  150   0.150     0.0000
   0.10  200     5.0   0    15    4     15   4   0.00025
ML02   7    LogSapWood        2.000  45     30  150   0.075     0.0000
   0.10  300     5.0   0    15    4     15   4   0.00075
ML02   7    LogHeartWood      2.000  45     30  150   0.075     0.0000
   0.10  200     5.0   0    15    4     15   4   0.00025
ML02   7    DeadBranch        2.000  45     30  200   0.150     0.0000
   0.10  200     5.0   0    15    4     15   4   0.00150
ML02   7    DeadCRoot         2.000  45     30  190   0.150     0.0000
   0.00  200     5.0   0    15    4     15   4   0.00000
ML02   7    StableFoliage     2.000  45     30  350   0.000     0.2000
  20.00  400     5.0   0    15    4     15   4   0.00100
ML02   7    StableWood        2.000  45     30  150   0.000     0.2000
   0.10  600     5.0   0    15    4     15   4   0.00100
ML02   7    StableSoil        2.000  45     15  100   0.000     0.0120
   0.00  100     5.0   0    15    4     15   4   0.00000
```

```
----------------------------------------------------------------------
File:  BurnKill.prm
----------------------------------------------------------------------
Burn and Kill parameters for fires - StandCarb model

Model File         Fire       %-Killed___  %-Burned___
#     #     Layer  Intensity  Above Below  Above Below

ML02     8  Herb   Hot         100   100    100   50
ML02     8  Shrub  Hot         100   100    100   10
ML02     8  LTree  Hot         100   100     10    5
```

```
ML02      8  UTree  Hot         100   100     5    2
ML02      8  Herb   Light       100   100   100    0
ML02      8  Shrub  Light        50    50    50    0
ML02      8  LTree  Light        80    80     5    0
ML02      8  UTree  Light        10    10     1    0
ML02      8  Herb   Medium       90    90   100   25
ML02      8  Shrub  Medium       75    75    75    5
ML02      8  LTree  Medium       90    90     7    2
ML02      8  UTree  Medium       50    50     2    1
```

File: SitePrep.prm

```
Site Prep parameters - StandCarb model

Model File                   Light  Medium  Hot
#     #    Pool              Burn   Burn    Burn

ML02   9   DeadFoliage        75.0   50.0     0.0
ML02   9   DeadFineRoot      100.0   75.0     0.0
ML02   9   SnagSapWood       100.0   85.0    50.0
ML02   9   LogSapWood         95.0   75.0    10.0
ML02   9   SnagHeartWood     100.0   95.0    75.0
ML02   9   LogHeartWood      100.0   90.0    50.0
ML02   9   DeadBranch         75.0   50.0     0.0
ML02   9   DeadCRoot         100.0  100.0    50.0
ML02   9   StableSoil        100.0  100.0   100.0
ML02   9   Stablefoliage     100.0   50.0     5.0
ML02   9   Stablewood        100.0   50.0     5.0
```

File: Harvest.prm

```
Harvest parameters - StandCarb model

                     Low                Medium             High
Model File           Utilization__      Utilization__      Utilization__
#     #   Treatment  %-Cut %-Taken      %-Cut %-Taken      %-Cut %-Taken

ML02  10     PCom        5      0         10      0          20     0
ML02  10      Com        5     50         10     90          30    95
ML02  10     CCut       80     80         95     90         100    95


                     Low                Medium              High
                     Utilization___     Utilization___      Utilization___
                     %-Taken MinVol     %-Taken MinVol      %-Taken MinVol


ML02  10     Salv       50    100          75     50          100     25
```

File: Herbicide.prm

```
Program    StandCarb
Data_File  Herbicide_Parms
Version    1

> Level of       %         %      %
> Effectiveness  Treated   Taken  Roots Die

         low       100       0       50
         medium    100       0       75
         high      100       0      100
```

File: Soil.prm

```
Soil parameters for StandCarb model

Model  File                   Water    Water  SoilWater
#      #     Soil Texture     PotAsym  Pot1   MaxPer

ML02   11    sand            0.00     0.25   25.0
ML02   11    loamySand       0.01     0.25   35.0
ML02   11    sandyLoam       0.02     0.25   35.0
ML02   11    loam            0.03     0.25   45.0
ML02   11    siltLoam        0.04     0.25   50.0
ML02   11    silt            0.05     0.25   50.0
ML02   11    sandyClayLoam   0.06     0.25   50.0
ML02   11    clayLoam        0.07     0.25   50.0
ML02   11    siltyClayLoam   0.08     0.25   50.0
ML02   11    sandyClay       0.09     0.25   45.0
ML02   11    siltyClay       0.10     0.25   60.0
ML02   11    clay            0.11     0.25   60.0
```

File: SiteIndex.prm

```
Bole growth efficiencies for Site Indexes - StandCarb model

            Site
Model File  Index    Site-1________  Site-2________  Site-3________
Site-4________  Site-5________
#     #     Species  High Med  Low   High Med  Low   High Med  Low
High Med  Low   High Med  Low

ML02 12     Abco     1.15 1.08 1.04  1.01 0.90 0.83  0.74 0.66 0.57
0.48 0.40 0.33  0.30 0.27 0.25
ML02 12     Abgr     1.00 0.95 0.85  0.80 0.75 0.70  0.65 0.59 0.52
0.48 0.42 0.36  0.30 0.24 0.18
ML02 12     Pico     1.10 1.00 0.91  0.83 0.75 0.69  0.62 0.55 0.49
0.43 0.37 0.31  0.25 0.20 0.15
```

```
ML02 12     Pimo     0.92 0.86 0.80  0.76 0.71 0.68  0.64 0.60 0.57
0.54 0.51 0.47  0.42 0.38 0.32
ML02 12     Pipo     1.92 1.65 1.50  1.45 1.22 1.06  0.89 0.75 0.65
0.55 0.45 0.41  0.35 0.30 0.25
ML02 12     Pisi     1.70 1.60 1.52  1.44 1.35 1.27  1.13 1.00 0.92
0.84 0.75 0.65  0.56 0.48 0.40
ML02 12     Psme     1.11 1.07 1.02  0.97 0.92 0.86  0.81 0.74 0.67
0.58 0.52 0.47  0.41 0.36 0.30
ML02 12     Tshe     1.60 1.50 1.40  1.27 1.21 1.11  1.06 0.98 0.88
0.79 0.68 0.61  0.51 0.44 0.33
ML02 12     Sese     1.60 1.41 1.33  1.23 1.07 0.98  0.84 0.73 0.66
0.59 0.51 0.42  0.38 0.35 0.30
```

Appendix B. Harvest results.

Treatment titles include artificial (art) and natural (nat) regeneration, GE (f), and thinning (t). The types of harvest are clearcutting (Ccut) and commercial thinning (Cthin) with the age when they occur shown near to them.

50 and 70-year rotations.

Treatment	Type of Harvest	Harvest m3/ha	Treatment	Type of Harvest	Harvest m3/ha
50art	Ccut 50	505.34	70art	Ccut 70	680.07
50art_f	Ccut 50	629.63	70art_f	Ccut 70	844.84
50art_ft	Cthin 30	95.31	70art_ft	Cthin 30	83.88
	Ccut 50	558.38		Cthin45	138.67
				Ccut 70	699.47
50art_t	Cthin 30	76.06			
	Ccut 50	448.09	70art_t	Cthin 30	67.34
				Cthin45	111.46
50nat	Ccut 50	462.91		Ccut 70	562.39
50nat_f	Ccut 50	574.60	70nat	Ccut 70	645.42
50nat_ft	Cthin 30	75.10	70nat_f	Ccut 70	801.70
	Ccut 50	519.30			
			70nat_ft	Cthin 30	65.14
50nat_t	Cthin 30	59.87		Cthin 45	127.06
	Ccut 50	415.87		Ccut 70	676.66
			70nat_t	Cthin 30	51.75
				Cthin 45	101.62
				Ccut 70	542.86

90 and 110-year rotations.

Treatment	Type of	Harvest	Treatment	Type of	Harvest
	Harvest	m3/ha		Harvest	m3/ha
90art	Ccut 90	828.24	110art	Ccut 110	942.48
90art_f	Ccut 90	1031.26	110art_f	Ccut 110	1170.98
90art_ft	Cthin 30	77.31	110art_ft	Cthin 30	73.62
	Cthin 45	135.30		Cthin 45	133.54
	Cthin 60	167.49		Cthin 60	166.70
	Ccut 90	809.65		Cthin 80	206.32
				Ccut 110	865.66
90art_t	Cthin 30	61.67			
	Cthin 45	108.59	110art_t	Cthin 30	58.49
	Cthin 60	134.62		Cthin 45	107.02
	Ccut 90	651.29		Cthin 60	133.88
				Cthin 80	165.83
90nat	Ccut 90	800.80		Ccut 110	696.60
90nat_f	Ccut 90	997.57	110nat	Ccut 110	923.95
90nat_ft	Cthin 30	60.11	110nat_f	Ccut 110	1149.00
	Cthin 45	124.28			
	Cthin 60	160.53	110nat_ft	Cthin 30	57.30
	Ccut 90	793.92		Cthin 45	122.47
				Cthin 60	159.69
90nat_t	Cthin 30	47.85		Cthin 80	201.44
	Cthin 45	99.56		Ccut 110	857.72
	Cthin 60	128.94			
	Ccut 90	638.37	110nat_t	Cthin 30	46.43
				Cthin 45	99.01
				Cthin 60	128.76
				Cthin 80	162.22
				Ccut 110	690.14

130 and 150-year rotations.

Treatment	Type of Harvest	Harvest m3/ha	Treatment	Type of Harvest	Harvest m3/ha
130art	Ccut 130	933.37	150art	Ccut 150	1007.68
130art_f	Ccut 130	1159.02	150art_f	Ccut 150	1244.62
130art_ft	Cthin 30	72.84	150art_ft	Cthin 30	72.85
	Cthin 45	133.21		Cthin 45	133.24
	Cthin 60	166.61		Cthin 60	166.65
	Cthin 80	206.37		Cthin 80	206.43
	Cthin 100	228.73		Cthin 120	274.00
	Ccut 130	828.45		Ccut 150	929.07
130art_t	Cthin 30	58.49	150art_t	Cthin 30	58.63
	Cthin 45	107.10		Cthin 45	107.21
	Cthin 60	133.97		Cthin 60	134.07
	Cthin 80	165.96		Cthin 80	166.05
	Cthin 100	183.12		Cthin 120	220.80
	Ccut 130	664.94		Ccut 150	745.53
130nat	Ccut 130	924.55	150nat	Ccut 150	992.26
130nat_f	Ccut 130	1146.08	150nat_f	Ccut 150	1237.40
130nat_ft	Cthin 30	56.59	150nat_ft	Cthin 30	57.39
	Cthin 45	122.32		Cthin 45	122.69
	Cthin 60	159.57		Cthin 60	159.77
	Cthin 80	201.34		Cthin 80	201.44
	Cthin 100	224.48		Cthin 120	273.69
	Ccut 130	824.24		Ccut 150	915.99
130nat_t	Cthin 30	45.61	150nat_t	Cthin 30	46.13
	Cthin 45	98.23		Cthin 45	98.60
	Cthin 60	128.25		Cthin 60	128.38
	Cthin 80	161.89		Cthin 80	161.86
	Cthin 100	180.07		Cthin 120	220.31
	Ccut 130	664.34		Ccut 150	741.20

Partial harvest including group-tree selection and single-tree selection with species of PSME (Douglas fir) and TSHE (Western Hemlock).

Treatment	Type of Harvest	Species	Harvest m3/ha
Group selection	Regulate 90	PSME	176.12
	Regulate 120		213.66
	Regulate 150		240.52
	Group every 30 Age 90	PSME	138.40
	Group every 30 Age 90	TSHE	47.92
Single-tree selection	Regulate 50	PSME	87.92
	Regulate 70		129.66
	Regulate 90		161.84
	Regulate 110		189.34
	Regulate 130		193.28
	Partial every 20 Age 100	PSME	33.44
	Partial every 20 Age 100	TSHE	137.36

Appendix C. DEA analysis results.

Results files from OnFront runs. All 48 regimes are included with artificial (a) and natural (n) regeneration, GE (f), and thinning (t). Carbon balance is in MgC/ha. SEV is in $/ha. Efficient treatments selected by DEA with efficiency score of 1.00 are marked with grey.

	Obs	**Fo(x,y) | N,S)**	**x1**	**y1 (S,Yes)**	**y2 (S,Yes)**
			Input	Carbon	SEV 3.5
1	50a	1.24	1	383.43	5894.26
2	50af	1.02	1	453.34	7348.45
3	50aft	1.00	1	428.29	7904.30
4	50at	1.22	1	363.87	6332.68
5	50n	1.26	1	351.13	6087.75
6	50nf	1.06	1	413.88	7376.34
7	50nft	1.01	1	393.58	7825.28
8	50nt	1.23	1	335.99	6406.84
9	70a	1.33	1	471.19	3970.24
10	70af	1.10	1	559.81	4933.80
11	70aft	1.01	1	507.25	6729.17
12	70at	1.23	1	428.31	5406.47
13	70n	1.33	1	442.12	4411.42
14	70nf	1.12	1	520.70	5316.95
15	70nft	1.03	1	477.10	6852.21
16	70nt	1.24	1	404.18	5616.91
17	90a	1.32	1	545.18	2521.93
18	90af	1.10	1	649.47	3143.51
19	90aft	1.02	1	565.24	5930.39
20	90at	1.23	1	479.60	4758.33
21	90n	1.34	1	517.89	3063.19
22	90nf	1.13	1	617.27	3660.86
23	90nft	1.02	1	541.09	6117.54
24	90nt	1.23	1	457.06	5032.10
25	110a	1.26	1	609.13	1426.31
26	110af	1.05	1	724.99	1773.74
27	110aft	1.00	1	610.06	5550.98
28	110at	1.21	1	515.85	4448.20
29	110n	1.27	1	583.65	2017.20
30	110nf	1.07	1	696.97	2357.10
31	110nft	1.00	1	589.55	5763.15
32	110nt	1.20	1	498.44	4770.70
33	130a	1.22	1	658.79	446.68
34	130af	1.02	1	787.83	555.85
35	130aft	1.00	1	640.17	5143.96
36	130at	1.20	1	541.75	4129.79

37	130n	1.22	1	638.56	1060.69
38	130nf	1.03	1	761.54	1165.13
39	130nft	1.00	1	623.28	5357.02
40	130nt	1.19	1	527.06	4428.24
41	150aft	1.00	1	682.96	4515.72
42	150at	1.20	1	575.78	3631.07
43	150n	1.19	1	670.78	591.48
44	150nf	1.00	1	802.73	588.76
45	150nft	1.00	1	667.48	4750.02
46	150nt	1.19	1	561.47	3940.36
47	Group	1.46	1	543.94	560.55
48	Single	1.48	1	489.08	2171.99

Only 25 regimes without GE are included.

	Obs	Fo(x,y) | N,S)	x1	y1 (S,Yes)	y2 (S,Yes)
			Input	Carbon	SEV 3.5
1	50a	1.02	1	383.43	5894.26
2	50at	1.00	1	363.87	6332.68
3	50n	1.04	1	351.13	6087.75
4	50nt	1.00	1	335.99	6406.84
5	70a	1.12	1	471.19	3970.24
6	70at	1.02	1	428.31	5406.47
7	70n	1.11	1	442.12	4411.42
8	70nt	1.02	1	404.18	5616.91
9	90a	1.10	1	545.18	2521.93
10	90at	1.02	1	479.60	4758.33
11	90n	1.12	1	517.89	3063.19
12	90nt	1.02	1	457.06	5032.10
13	110a	1.05	1	609.13	1426.31
14	110at	1.01	1	515.85	4448.20
15	110n	1.07	1	583.65	2017.20
16	110nt	1.00	1	498.44	4770.70
17	130a	1.02	1	658.79	446.68
18	130at	1.01	1	541.75	4129.79
19	130n	1.03	1	638.56	1060.69
20	130nt	1.00	1	527.06	4428.24
21	150at	1.00	1	575.78	3631.07
22	150n	1.00	1	670.78	591.48
23	150nt	1.00	1	561.47	3940.36
24	Group	1.23	1	543.94	560.55
25	Single	1.24	1	489.08	2171.99