Impacts of Thinning on Carbon Stores in the PNW: A Plot Level Analysis

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Final Report

College of Forestry
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25 May 2011

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Executive Summary

This report provides an analysis of forest carbon stores, fluxes and avoided emissions directly related to fuel reduction thinnings for sample plots in eastern and western Oregon.

Primary Goals

- Determine the level of on-site carbon storage under different thinning prescriptions and in different forest types.
- Analyze plot-level forest carbon pools and carbon fluxes over a 50-year period. Compare alternative thinning treatments with a no thinning scenario.
- Estimate the amount of carbon transferred to harvested wood products, carbon emissions of biomass burning for energy production, and avoided carbon emissions from not burning fossil fuels.
- Determine if revenue from harvested wood products from the thinning treatment could pay for the thinning under specified market and harvest unit assumptions for one thinning scenario (the "breakeven" scenario).

Methods

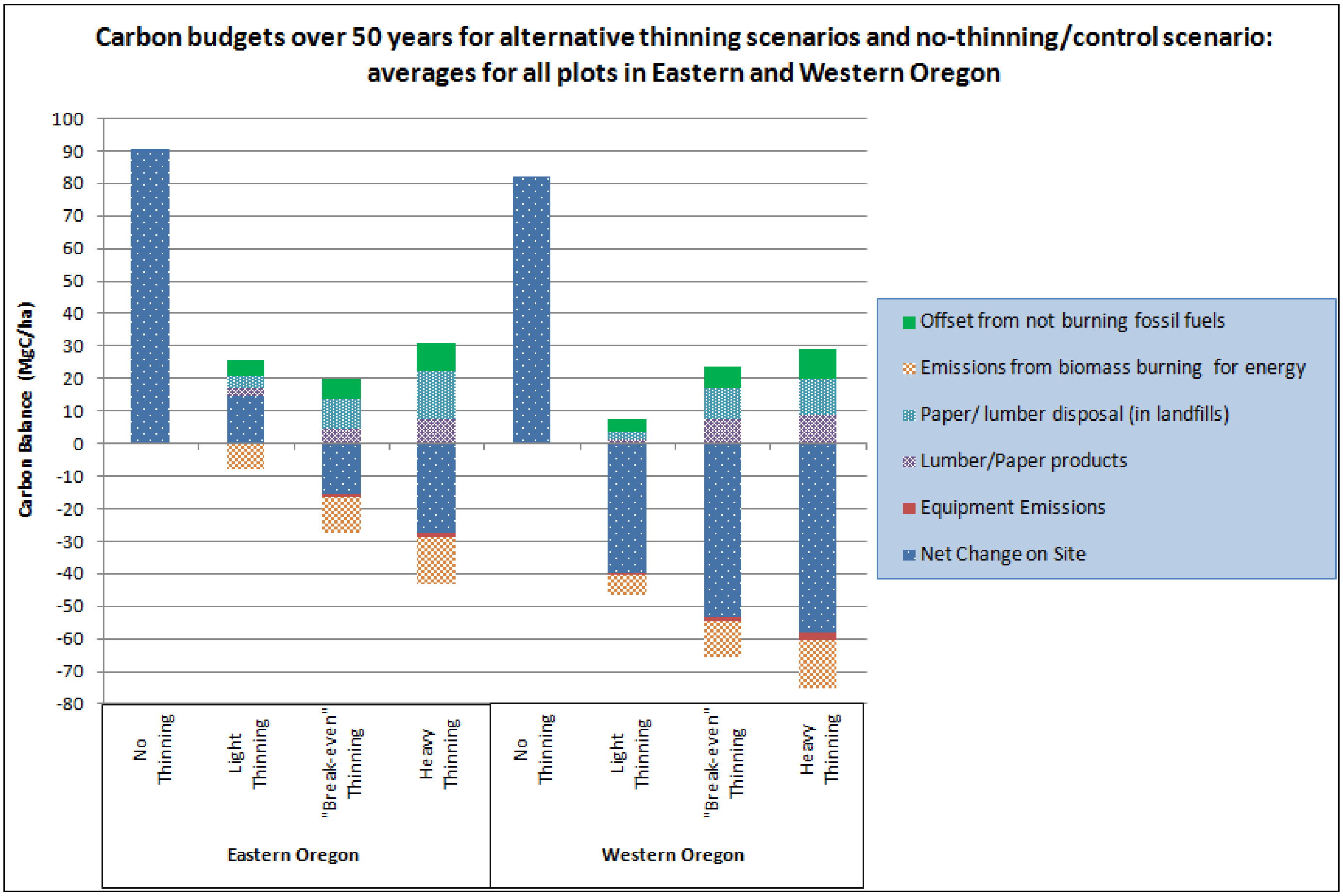
- Plots were chosen from the Forest Inventory and Analysis (FIA) National Program and the Current Vegetation Survey (CVS) to represent a range of common landscape types with stand conditions that show a potential for fuel reduction.
- Plots were all from Oregon, including the Eastern Cascade, Western Cascade, and Blue Mountain regions. A wide range of stand ages was included (21-269 years for Eastern Oregon/Blue Mountains and 10-220 years for Western Oregon).
- Thinning scenarios were developed to meet specified torching and crowning thresholds. All simulated thinnings use a "thin from below" (low thinning) approach. A control (no harvest scenario) is compared to different treatments.
- Carbon pools were estimated using the Fire and Fuels Extension (FFE) of the Forest Vegetation Simulator (FVS) with manual adjustments and additions to address known model limitations.
- Estimated harvest costs were based on the Fuel Reduction Cost Simulator (FRCS-West). Estimated timber revenues were based on ODF data.

Findings

- Forest carbon pools always immediately decreased as a result of a fuel reduction thinning, with larger differences in total carbon pools resulting from heavier thinning treatments.
- After thinning, forest carbon pools (both total and standing live aboveground) remain lower throughout a 50-year period for all simulated plots in eastern and western Oregon. The difference in total carbon pools between a thinned and unthinned plot is dependent on the level of live standing tree inventory reduction. A heavier thin tends to reduce carbon pools more than lighter thins throughout a 50-year simulated period.
- Carbon pool estimates for thinned stands were still lower than unthinned stands even after accounting for carbon transfer to wood products and avoided emissions from fossil fuels for energy production. After simulating growth

in the stands for 50 years the average difference in net carbon balance between unthinned and thinned plots for the three age groups ranged between 73.5– 103.4 MgC/ha in Eastern Oregon to 121.8 – 128.6 MgC/ha in Western Oregon. Carbon losses on site account for the bulk of the effect of thinning on carbon. Carbon retention in wood products and avoided emissions from fossil fuels tend to offset the equipment emissions and emissions from burning biomass for energy, but not the loss of carbon from forest on site.

- The following figure (adapted from Table 15) shows that, regardless of the single-entry thinning regime used, the “No Thinning” scenario resulted in the most carbon remaining on-site following 50 years. The figure accounts for emissions from equipment and emissions from biomass burning, and also accounts for paper/lumber products sequestered after 50 years, and offsets from burning biomass for energy instead of fossil fuels. The “Net Change” in the graph includes all gains and losses in carbon on-site 50 years after either no thinning, or 50 years following a thinning from a single entry.


Carbon budgets over 50 years for alternative thinning scenarios and no-thinning/control scenario: averages for all plots in Eastern and Western Oregon

- For the plots examined, it is generally possible to reach specific fuel reduction goals with revenues exceeding treatment costs. There are notable exceptions in younger plots, particularly in plots with relatively few larger trees (as measured by DBH). If administrative costs are included, treatment costs may exceed harvest revenues on federal lands. Financial viability is significantly affected by many stand-dependent variables, including current stand structure, average distance of wood from roadside, average distance of stand to mill/plant, and current market prices.

- Burning biomass from forest fuel reduction thinnings results in avoided carbon emissions from fossil fuels. Due to relatively low energy density, biomass has greater carbon emissions from the boiler per energy unit produced (CO_2 emissions per kWh or BTU produced) when compared to carbon emissions from fossil fuels (coal, natural gas) per energy unit produced.
- All thinning scenarios on all plots without exception resulted in a significant loss of carbon relative to a no-thinning scenario. This suggests that the findings may be applicable to other forest types and thinning prescriptions.

Key Assumptions and Limitations

Our key assumption is that the life cycle analysis of carbon stores and fluxes begins with initial carbon stores in the stand prior to thinning as described by Maness 2009. In other words, our analysis starts with existing forest condition and measures the net change in carbon stores due to the thinning treatments. This assumption contrasts with other studies (e.g., Lippke et al. 2004) that start with bare ground as a system boundary. The results (and potentially the conclusions) can be dramatically affected by the choice of system boundary.

- Not considered in this analysis:
    - Effects of fire on carbon pools and flux. This includes any potential post-thin treatments. In this study, we do not estimate whether carbon emissions from prescribed fire and/or wildfire would (over repeated cycles) be higher or lower after thinning.
    - Soil carbon and fine roots (roots less than 2 mm in diameter).
    - Emissions due to consumption of electric power in lumber and paper production. Including these emissions would increase the greenhouse gas emissions for each of the thinning scenarios.
    - Disposal methods for wood products (e.g., recycling and use as biofuel). In this analysis, wood products are assumed either taken to a landfill or burned as an energy source.
    - Effects of climate change (e.g., temperature, precipitation).
    - Vegetation in-growth. This report assumes that in-growth is managed with regular treatment (e.g., with herbicides) that limits in-growth. If in-growth is allowed and fire is suppressed, estimates of carbon pools on-site may significantly increase, especially for longer time periods.
    - Emission reductions from substitution effects of wood products for more energy intensive alternative building materials (such as concrete, brick, or steel). Inclusion of substitution effects would decrease carbon emissions for thinning scenarios.

Because this is a plot-level study, where plots were chosen based on specific criteria (stand age, specific stand structures, specific dominant species), study results cannot be extrapolated directly to a regional analysis. The analysis assumes that there is no re-entry onto the site in the next 50 years. The stand projection is shown for illustrative purposes only; it is not intended to be a management prescription.

Future Work

There are several potential areas of study that can support and enhance work begun in this report. This would close the gap on some of the limitations presented within this report.

An expanded analysis would improve regional understanding of forest carbon stores in varying conditions. Inclusion of one or more of the following variables would not only expand the scope of this report but also enhance the results presented from the study.

- Effects of prescribed fire and wildfire intensity and frequency on carbon stores.
- Effects of strategic placement of thinning on carbon stores for larger areas.
    - Effects of thinning in easily accessible areas (e.g., near roads) vs. thinning over larger areas.
    - Urban thinning.
- Effects of varying the price for biomass.
    - Sensitivity analysis of biomass price (and potential impact of financial subsidies on thinning regime).
- Inclusion of thinning regimes as part of a broader strategy to improve forest health or in response to insects/disease (e.g., beetle kill).
- Establish a more detailed time profile of carbon. This would include an annual carbon budget over a given time frame instead of a carbon budget at less frequent intervals.
- Since all thinning treatments reduced carbon storage over a 50-year period, it is possible that additional entries would further reduce carbon stores. In order to more fully understand the effects, a more complete forest management should be included in future work, instead of a single management action (thinning).

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Introduction

There is growing interest in improving the resilience of forests to fire, insects, and disease in the Pacific Northwest and in biomass recovery for energy production (Graham et al. 2004; Lord et al. 2006). There has also been extensive analysis and discussion on the impact of forest management (and other disturbances) on forest carbon stores and fluxes (Krankina and Harmon 2006). Other studies have developed regional estimates of forest carbon stores (Dushku et al. 2007).

The purpose of this study is to determine the level of on-site carbon stores at a plot level under different fuel reduction thinning operations in different forest types in Oregon. Some off-site carbon estimates are made as well. A collection of relatively densely stocked plots was chosen from five Oregon counties in the Western and Eastern Cascades, southwest Oregon, and the Blue Mountains region.

The carbon pools of each plot for thinned and unthinned scenarios are projected and compared. The resulting simulated carbon stores and carbon fluxes from this model are not intended to be extrapolated to regional or landscape levels, and are restricted to a plot-level analysis. To simplify the analysis, we limit our examination to a subset of possible product end uses. Therefore, the model does not comprehensively describe all potential carbon fluxes. A life cycle analysis would more fully define carbon transfers for alternative product uses.

The report is organized as follows:

- Plot-level model approach and design
- Choice of plot-level simulator for tree growth
- Carbon fluxes
- Scope of this study
- Plot selection
- Detailed example plot to show methodology
- Broader analysis of plots, fewer details shown
- Overall results from analysis
- Discussion
- Suggestions for future analysis
- References
- Appendices (primarily detailed results)

Suggestions for further research are included. The reader is encouraged to use the reference section to access more detailed information. Some of the topics discussed in this report (such as fuel reduction for wildfire mitigation) currently either have mixed results or may lack scientific consensus, and we identify these areas when appropriate.

Model Overview

This section describes a model that simultaneously analyzes the economic feasibility of a fuel treatment (thinning) and the impact of the forest treatment on forest carbon pools and fuel loading at a plot level. For each plot, a customized treatment is implemented following an analysis of the current situation using several criteria. The procedure and results for an example plot are described in detail and the procedure is then applied to all plots. The analysis groups plots into age groups and regions, then notes differences between groups and possible causes for these differences.

The objectives for this study integrate both carbon accounting and economic considerations.

Model objectives include (not necessarily in order of importance):

- Implement thinning regimes for each plot that reduce modeled fuel loading.
- Identify and quantify carbon losses in the carbon pools that occur for each plot after thinning.
- Estimate carbon fluxes for removed trees and any potential carbon displacement by replacing fossil fuels with biomass for energy usage.
- For each plot, include one breakeven forest treatment with a forest harvest system (including transportation, processing, move-in, and setup costs) that, when implemented, does not result in a net financial loss for the landowner. To facilitate harvesting cost accounting, harvesting system choice was limited to a whole tree harvesting system. The harvesting system choice may affect the breakeven thinning scenario, but does not significantly affect the relative carbon budget for the light and heavy thinning scenarios.

The parameters for the model are customized for each plot. The general construction of the model and the interaction between objectives is shown (Figure 1).

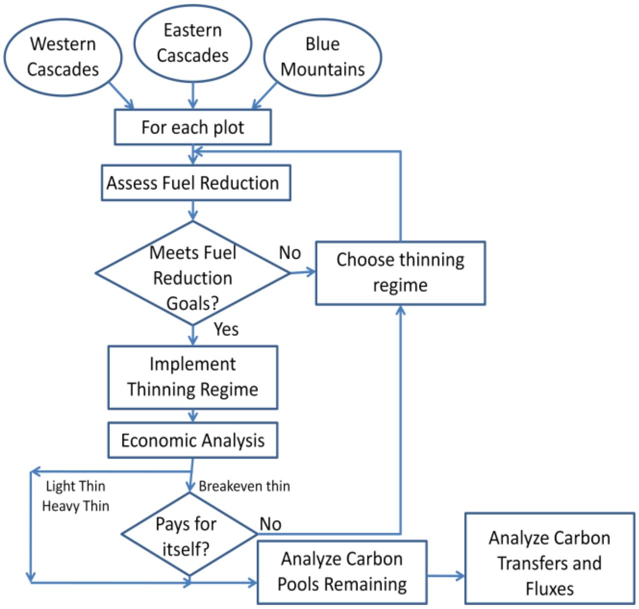

Figure 1. Model flowchart with objective interaction. Light Thin and Heavy Thin scenarios are not expected to pay for themselves, but the Breakeven Thin is expected to pay for itself.

Thinning Prescriptions

There are many potential thinning prescriptions that can vary due to landowner objectives and constraints. Objectives may include (1) increased wood production, (2) increased resistance to fire, insects and disease, and (3) enhancement or control of plant and animal habitats (Nyland 2002; Graham et al. 2004). The purpose of this report is not to advocate one thinning prescription over another, but to show carbon stores and fluxes given one set of objectives. A regional plan would likely integrate multiple spatially-dependent objectives into a larger scope. Several thinning intensities are simulated, ranging from a light thin to heavier thinnings.

To maintain consistency between plots in this analysis, the general criteria for thinning each plot includes:

- Stands are to be thinned from below (low thinning), where smaller diameter trees are removed from dense stands. Pollet and Omi (2002) have shown this thinning regime to be effective in reducing crown fire severity in ponderosa pine.
- Since the smallest trees removed often do not “pay for themselves” in a thinning (USFS 2005), a proportion of larger diameter trees (up to 20” DBH) may also be removed in the breakeven scenarios or to achieve low stocking levels, but the largest trees within a plot are left if possible. Largest trees are determined by diameter at breast height (DBH), which is a diameter estimate 4.5 ft (1.37 m) from the ground.
- Brush and smaller trees in the understory are identified as a potential fuel ladder, and smaller vegetation not removed from the stand is trampled or crushed in the simulation (this includes all trees <3” DBH).
- Treated plots should meet both fuel hazard measurement goals and, for the breakeven scenario, economic requirements immediately following the thinning, if possible.

It is not implied that this thinning prescription should be applied across a more complex landscape level. This prescription strategy is simulated only for these isolated plots. A thinning prescription at a regional scale (e.g., Finney et al. 2006) could consider many factors, including

- Long-term prescription alternatives for the stand.
- Prescriptions/species/ fuel loadings for surrounding stands
- Fire hazards that are not necessarily measured by fuel loading (e.g., topography)
- Desired combination of tree species and stand structures (e.g., Fiedler et al. 1998)
- Wildlife considerations (e.g., endangered species, fish/bird/animal habitat requirements) (Hayes et al. 1997)
- Susceptibility to insects and/or disease (Hessburg et al. 1993)
- Watersheds and proximity to riparian areas
- Aesthetics and recreational potential (Scott 1996)
- Accessibility to harvesting equipment

Thinning and fuels treatment only temporarily reduces fuel loading within a stand. In order to be more effective over the long term, it is necessary to implement a strategy (such as prescribed burning) that would periodically reduce surface fuels (Weatherspoon 1996) and possibly to re-enter the stand for periodic thinnings (Keyes and O'Hara 2002). The carbon fluxes associated with a prescribed burn or re-entries is not included in this model. Even though fire behavior may be more influenced by weather conditions and topography (Bessie and Johnson 1995), fuel loading is still an important variable affecting stand mortality in a wildfire. From a strict carbon savings perspective, there are currently two views concerning the effects of wildfire following a fuel reduction treatment (Ryan et al. 2010):

- Some studies and models show less carbon loss from thinned stands (compared to unthinned stands) following a crown fire.
- Some studies and models show that in most forest types, thinned stands have less carbon than unthinned stands at a landscape level following a crown fire.

Regional research comparing Eastern and Western Cascades suggests that if thinning ever reduces total net carbon loss from thinning combined with subsequent wildfire, it would likely only be in Eastern Cascade ponderosa pine stands with dense understory (Mitchell et al. 2009).

Choice of Model to Project Forest Carbon

There are several models developed to simulate forest carbon – for example, Harmon and Marks (2002) simulate forest carbon on a landscape level. This analysis is conducted using a growth and yield model. There are several forest growth and yield models available for the Pacific Northwest region (Marshall 2005). The Forest Vegetation Simulator (FVS) was chosen as the growth and yield model for this study – it is commonly used for both national and regional stand projections, has an integrated graphical user interface (SUPPOSE – Crookston 1997), and also has a built-in Fire and Fuels Extension (FFE - Reinhardt and Crookston 2003) that has been used to estimate forest carbon pools over time (e.g. Manomet 2010).

Carbon Fluxes

Figure 2 shows an example of carbon stores and associated carbon fluxes used in calculations for this report.

The stores are calculated as follows:

- Total Carbon on Site – Carbon on site in any given year.
- Biomass for Energy – Carbon processed (burned) for biomass energy in the year of harvest. Combination of slash/small trees (primary source) and residues from the lumber/paper manufacturing process (secondary source).
- Lumber Products - Carbon store transferred to lumber products from harvest and manufacturing process.
- Paper Products - Carbon store allocated to paper products from harvest and manufacturing process.
- Paper/Lumber Residue – Carbon store transferred to paper/lumber process, but not converted to paper or lumber products. Some of this store is allocated to biomass for energy, and the remaining portion is assumed disposed in a landfill (1% decay rate assumed – decay rate used in other models: e.g., Hennigar et al. 2008).
- Landfill – Carbon store to where paper and lumber products are assumed transferred following use. The landfill decay rate is assumed to be 1%.

Some other carbon fluxes are not specifically quantified in this report (e.g., impact of thinning on soil carbon, fossil fuel emissions associated with energy needs of product manufacturing, effects of substitution of wood products for more energy-intensive materials). Accounting for these additional C fluxes is a complicated process and is beyond the scope of this report. However, these factors collectively would not be expected to change the overall conclusions of the study.

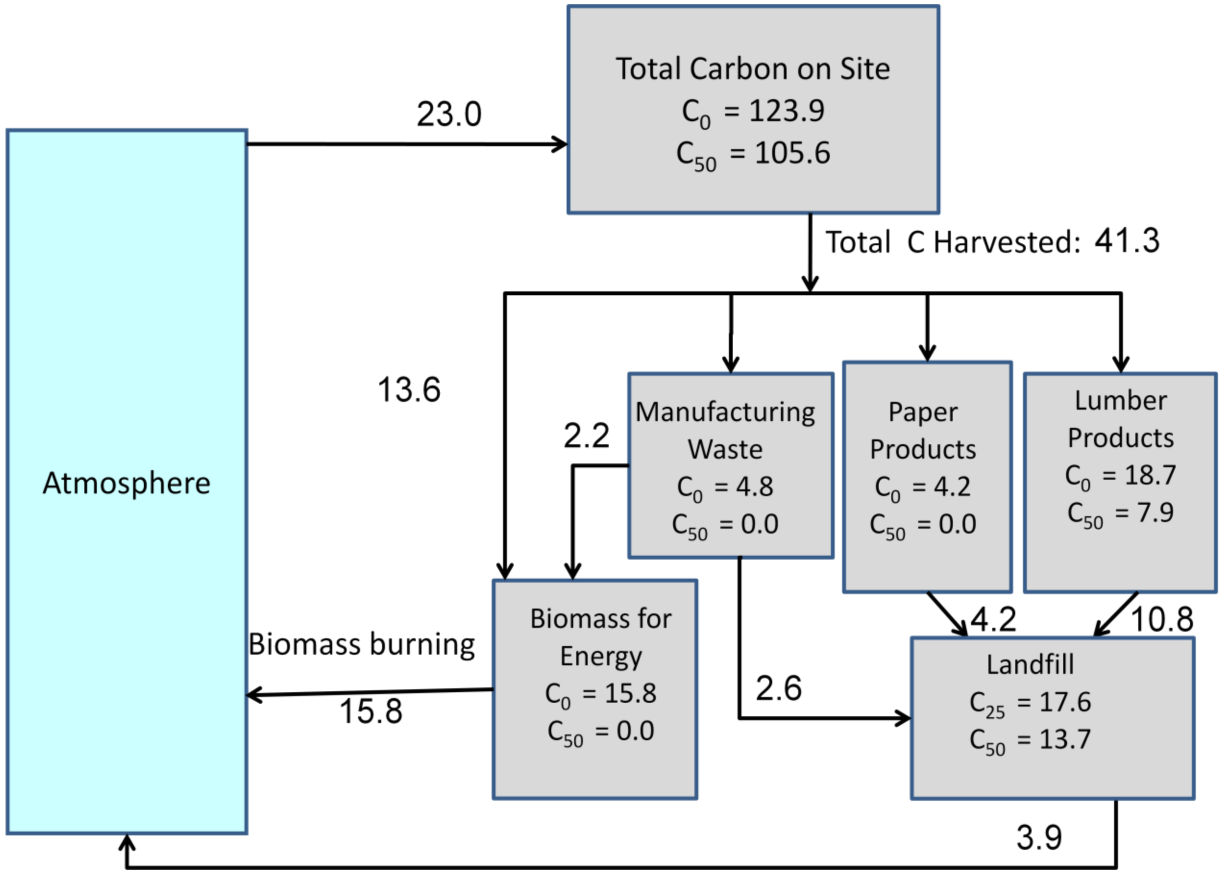

Figure 2. Calculated carbon stores and fluxes associated with a thinned plot. Example for "Heavy thinning scenario". All carbon stores are in MgC/ha. Subscripts indicate year after thinning. For example, C_0 is the carbon store in year 0 immediately following a thinning. The two fluxes accounted for (but not shown) are (1) fossil fuels emissions in harvest operations (1.7 MgC/ha) and offset of fossil fuels from burning biomass (8.3 MgC/ha).

Carbon Accounting Methods Used in this Report

Carbon pools are calculated at 1 year intervals over a 50 year timeframe for each selected plot with the goal to account for all C emissions and sequestration associated with thinning and no-thinning scenarios (Figure 2). The results are shown in Appendix F and the summary carbon budget is calculated by summing up change over 50 years in the following C pools:

- C store on site
- C removed from site by harvest:
    - paper and lumber products
    - manufacturing waste
    - product and waste disposal in landfills
    - biomass for energy

In addition two fluxes (or changes in fossil fuel C store resulting from thinning) were accounted for:

- Emissions from equipment
- Avoided carbon emissions when burning biomass for energy instead of fossil fuels.

Carbon Store on Site

Forest carbon pools are divided into seven categories in the FVS FFE extension:
(1) Standing live trees (above ground),
(2) Below ground live,
(3) Standing dead trees,
(4) Below ground dead,

(5) Forest floor,
(6) Downed dead wood, and
(7) Shrubs and herbs.

The FVS-FFE extension simulates periodic carbon estimates for each of the seven categories. The FVS-FFE biomass estimates (and subsequent carbon estimates) do not include stem bark biomass or stump biomass. Both components have been manually added (using allometric equations) for each tree. Additional details of the model (including allometric equations) are included in Appendix E.

The FVS-FFE model simulations for each thinning prescription projects the following transfers of carbon:

- C in roots of harvested trees is added to below ground dead store.
- C from slash, logging residue, and whole trees ≤3” DBH left on site following a thinning scenario is added to downed dead wood.
- Default regional decay rates with the FVS-FFE model are used for slash/duff/litter.
- C removed from the site is reported as “Carbon removed”.

Carbon Fluxes from Thinning Operations

Sources of carbon as a direct result of a thinning operation include carbon emissions from logging equipment (both in the field and on the landing) and carbon emissions from trucks/chip vans. There are several sources of carbon for a thinning scenario, and estimates are based on machine fuel consumption. We assumed all equipment is powered by diesel engines – approximately 6.06 lbs of C are emitted for each gallon of diesel fuel (EPA 2005).

Once a thinning scenario is defined for a given forest stand (e.g., 30 green tons removed/acre, 10% slope, 1 acre/day, 8 hr day, 90 minutes to transport to mill/plant), the amount of carbon released to the atmosphere as part of a thinning scenario can be estimated. Diesel consumption rates vary based on work-load. We estimate fuel consumption rates using an engine work-load factor (Caterpillar 2010), where a load factor of 1.0 indicates that the engine is continuously producing full rated horsepower. For thinning scenarios in this report, relatively low load factors are assumed (0.4-0.5) except for plots with steeper ground slopes, where higher factors are assumed. Diesel is assumed to be 7 lbs/gal, and diesel usage is estimated at 0.4 lbs per hp-hr. Carbon emissions from harvesting equipment can be estimated at a plot level (Table 1).

Table 1. Example of estimated tons of carbon emitted during harvesting and transport for each ton of carbon removed from a thinning. Harvest and transport estimates are based on fuel consumption (lbs) per productive machine hour (PMH). Harvested wood is at 50% moisture content.

Equipment	Est. Maximum Power (HP)	Est. Diesel (gal/PMH)	Est. C (lbs/PMH)	Productivity (tons C from forest/PMH)	Operations (tons emitted/tons from forest)
Feller/buncher*	240	5.49	33.26	3.75	**0.0177**
Grapple skidder*	120	2.74	16.63	3.75	**0.0089**
Log loader	200	4.57	27.72	7.50	**0.0037**
Chipper	300	17.14	103.94	15.00	**0.0069**
Processor	200	4.57	27.72	7.50	**0.0037**
Log Truck	400	8.00	48.50	4.33	**0.0112**
Chip van	400	8.00	48.50	4.33	**0.0112**
Total					**0.0633**

*Assuming that 30 green tons/acre are processed, at 1 acre/day.

In this example, an estimated 0.06 tons (120 lbs) of carbon are emitted by the thinning activity for each ton of carbon extracted (assuming wood that is extracted has 50% moisture content). This estimate would increase for trees farther from the road, and for sites farther from mills/plants decrease for a thinning nearer to the road or the mill. The emissions estimate assumes that chipping is done on site – if forest residues are transported then chipped with an electric-powered chipper (more efficient), overall carbon emissions would likely decrease depending on load density of the transported unchipped residues to the chipping location.

Carbon in harvested material

Carbon removed from each plot by thinning was estimated with FVS. The allocation of removed biomass into forest products depends on many factors, including regional market supply/demand, proximity of processing facilities, wood product quality/species, log sizes, and mill efficiencies. Several assumptions are made in order to estimate final wood products.

In the model, trees are separated into 3 categories: (1) smallest trees (<3" diameter over bark at breast height), (2) small trees (>3" and < 6" diameter over bark at breast height) and (2) larger trees (≥ 6" diameter over bark at breast height). Smallest trees are trampled and left in the field. Small trees have only one product use (biomass for energy), but the end products for larger trees are more diverse. Since most of the trees removed in thinning are relatively small, it is assumed that all logs greater than 6" DBH are transported to a sawmill and then sawn into dimensional lumber, with residues used for paper and energy or disposed of in a landfill.

Wood products are separated as follows:

- Hog fuel ("dirty" chips): All smaller trees (< 6" DBH) and the branches/tops for larger trees that are transported to the landing are fed into a chipper and processed into chips.
- Primary sawmill products: Include dimensional lumber.
- Mill residues: Include "leftover" portions not used in the primary product, such as bark, sawdust, planer shavings, and chips.
  - Bark – may be used for "beauty" bark, energy.
  - Sawdust – may be used for paper, particle board.
  - "Clean" chips – may be used for paper, particle board.

Estimates of sawmill residues and final products are available for Oregon (Brandt et al. 2006). The resulting estimates of sawmill outputs are based on a statewide average recovery factor of 2.07, which varies due to mill efficiency, log size, and scaling. The carbon allocations from mill gate to final product are used to estimate the carbon transferred to various wood products (Figure 3). We assume that lumber and paper products are separated as 62% toward lumber and 27% toward paper.

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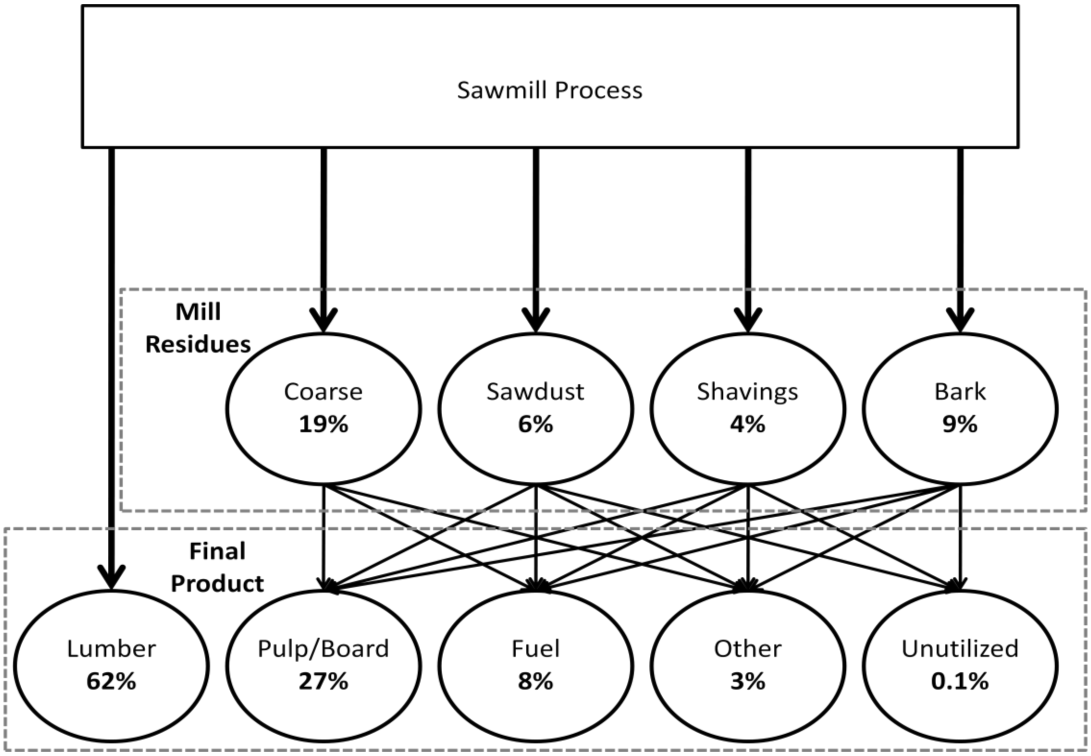


Figure 3. Estimated sawmill residues and final products (by weight), based on Brandt et al. 2006.

Manufacturing waste includes “Fuel”, “Other” and “Unutilized” from Figure 3 as well as carbon from the paper manufacturing process that is assumed not stored within paper. The “Fuel” portion is assumed used toward biomass for energy, and the remaining manufacturing waste is assumed transferred to landfill (with a 1% annual decay rate).

Carbon in wood products

The amount of carbon retained in wood products over time is estimated with an exponential function with set half-lives for each wood product. The method used in this report to estimate transferred carbon over time is similar to the “simple decay” method (Ford-Robertson 2003).

$$Sequestered\ Carbon\ (Year\ x) = \sum_{i=1}^{n} \text{Carbon}(\text{Year } 0)_{\text{i}} * \left(\frac{1}{1+\frac{\ln(2)}{\text{halflife}_{\text{i}}}}\right),$$

where $n = number\ of\ products$

There is a wide range of half-lives for wood products - Table 2 shows some examples (Skog and Nicholson 1998). This report takes a simple approach - paper products are assumed to have a half-life of 1 year, timber products a half-life of 40 years, and biomass for energy is assumed to be burned and emitted to the atmosphere within a year.

Table 2. Harvested wood product estimated half-life of carbon (years) for different end uses (Skog and Nicholson 1998).

End Use	Half-Life
Single-family homes(post 1980)	100
Pallets	6
Furniture	30
Paper (long-lived publications)	6
Paper (other)	1

Carbon in landfill

We assume that carbon that is not retained in wood products (both paper and lumber) is transferred to landfill. We make simplified calculations for this pool to estimate the amount at the end of 50-year projection period (while all other pools are estimated on an annual basis (Appendix F). The decomposition rate is 1% per year and the time interval is 25 years (half of 50-year projection period)

Carbon in slash harvested and utilized as source for energy

In the model for this study, all stems <3" DBH are "trampled" (using an FVS keyword) and left on site. This keyword affects crowning and torching index estimates; trampled stems contribute to the downed dead wood carbon pool. The amount of slash from larger trees (>3" DBH) removed from the forest in a mechanized logging operation varies widely. Removal rate estimates of slash from cut-to-length mechanized logging range from 50-75% (Mellström and Thörlind 1981; Sondell 1984).

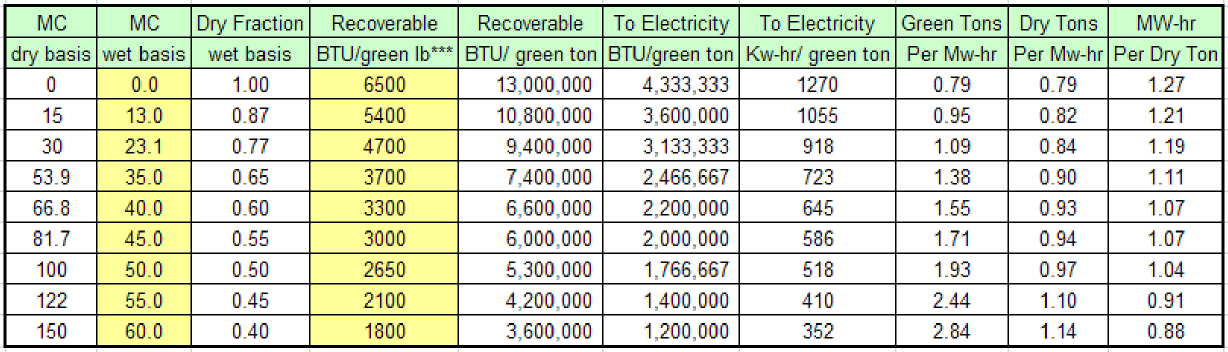
It is assumed that the removal rate of slash is 80%, using a whole-tree logging system for this study. We assume that the slash removed from site is transported and burned as biomass fuel, instead of piled and burned on site. Transportation costs are included in the model. The 20% of slash left on-site is included as downed-dead wood, and decays over time using default FVS regional decay rates.

In FVS, the torching and crowning indices are impacted by increased fuel loading from slash but the effects are seen only in the short term (less than 5 years) as the slash decays. The effect of slash removal on soil nutrients is an important site dependent factor that should be considered (e.g. Page-Dumroese et al. 2010), but an analysis is not included in this report.

Avoided carbon emissions - comparison of carbon emissions between biomass and other energy sources

Both heat and electricity can be extracted from biomass. The biomass input requirement per MW-hour for a stand-alone biomass electric power generation plant depends on biomass moisture content. The relationship between input biomass and output electric power can be found, assuming that 33% of energy output from the boiler can be utilized for electric power (Table 3). The dry tons of biomass required per MW-hour are a function of biomass moisture content.

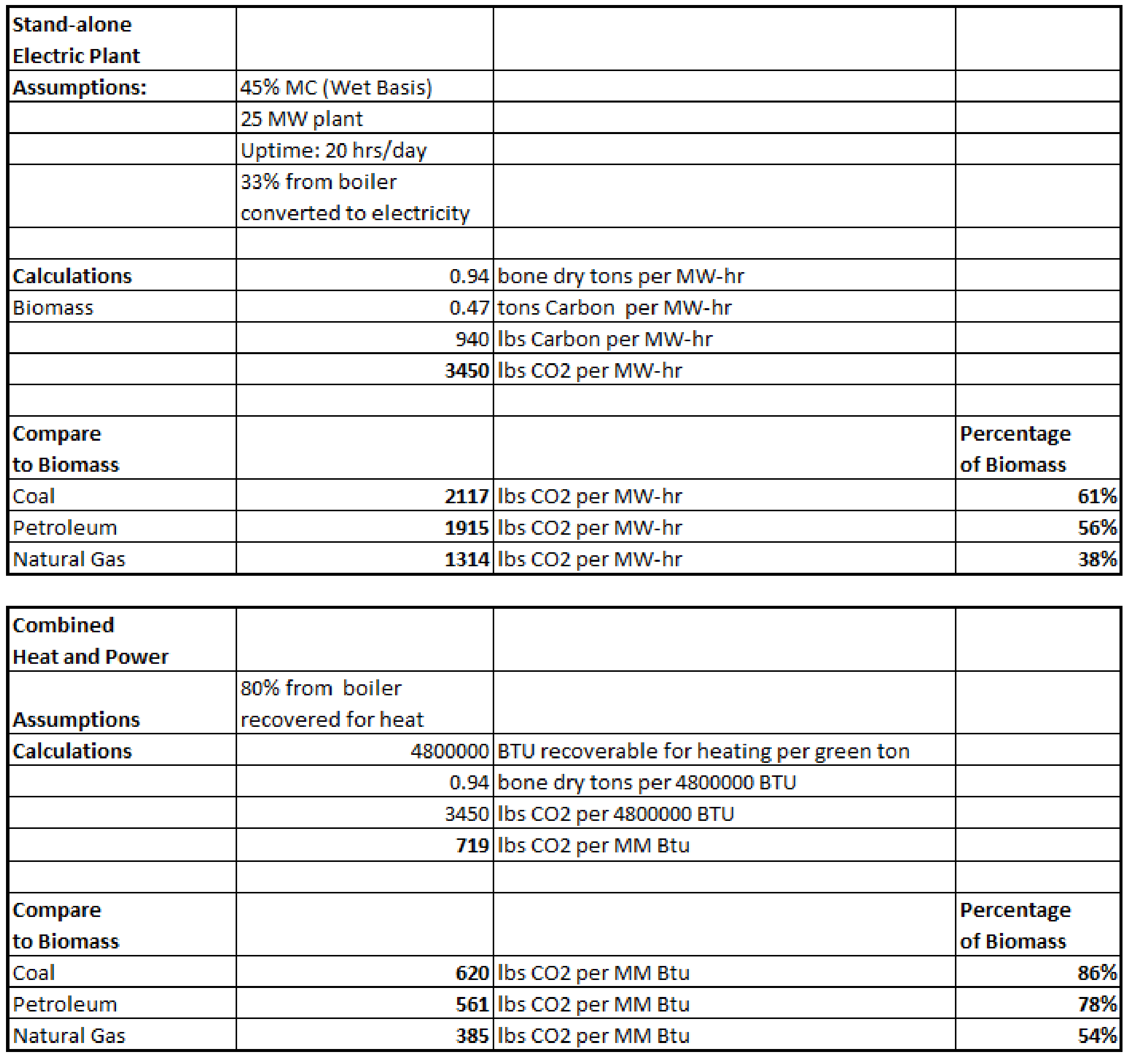
Table 3. Estimated forest biomass requirements as a function of wood moisture content.



MC	MC	Dry Fraction	Recoverable	Recoverable	To Electricity	To Electricity	Green Tons	Dry Tons	MW-hr
dry basis	wet basis	wet basis	BTU/green lb***	BTU/ green ton	BTU/green ton	Kw-hr/ green ton	Per Mw-hr	Per Mw-hr	Per Dry Ton
0	0.0	1.00	6500	13,000,000	4,333,333	1270	0.79	0.79	1.27
15	13.0	0.87	5400	10,800,000	3,600,000	1055	0.95	0.82	1.21
30	23.1	0.77	4700	9,400,000	3,133,333	918	1.09	0.84	1.19
53.9	35.0	0.65	3700	7,400,000	2,466,667	723	1.38	0.90	1.11
66.8	40.0	0.60	3300	6,600,000	2,200,000	645	1.55	0.93	1.07
81.7	45.0	0.55	3000	6,000,000	2,000,000	586	1.71	0.94	1.07
100	50.0	0.50	2650	5,300,000	1,766,667	518	1.93	0.97	1.04
122	55.0	0.45	2100	4,200,000	1,400,000	410	2.44	1.10	0.91
150	60.0	0.40	1800	3,600,000	1,200,000	352	2.84	1.14	0.88

Given the assumptions from Table 3, the carbon emissions from biomass-produced energy from a stand-alone unit can be estimated and compared to emissions from alternative sources of energy (USDOE 2010) (Table 4). The efficiency of a biomass plant depends on moisture content – the analysis in Table 4 assumes 45% moisture content for forest residues. Table 4 compares carbon emissions between energy source alternatives for biomass combined heat and power (CHP) units, assuming 33% electrical conversion from the boiler. Biomass fuel produces more CO_2 per MW-hour compared to other fossil fuel sources when used as a stand-alone source for power. The difference between biomass and fossil fuel is closer if electric power is not generated, and instead 80% of the energy from the boiler is used for heating. When comparing CO_2 output between forest biomass and fossil fuels, forest biomass has a higher CO_2 production per energy unit produced. This analysis applies only to boiler output, and does not include alternatives or other emissions for each energy source.

Table 4. CO2 output ratios of fossil fuels compared to wood biomass. (fossil fuel estimates from U.S. Dept. of Energy 2000). For example, natural gas releases 38% of CO2 per MW-hour of electricity or 54% of CO2 per MM BTU as compared to the wood biomass.



Stand-alone Electric Plant			
Assumptions:	45% MC (Wet Basis)		
	25 MW plant		
	Uptime: 20 hrs/day		
	33% from boiler converted to electricity		
Calculations	0.94	bone dry tons per MW-hr	
Biomass	0.47	tons Carbon per MW-hr	
	940	lbs Carbon per MW-hr	
	3450	lbs CO2 per MW-hr	
Compare to Biomass			**Percentage of Biomass**
Coal	**2117**	lbs CO2 per MW-hr	**61%**
Petroleum	**1915**	lbs CO2 per MW-hr	**56%**
Natural Gas	**1314**	lbs CO2 per MW-hr	**38%**

Combined Heat and Power			
Assumptions	80% from boiler recovered for heat		
Calculations	4800000	BTU recoverable for heating per green ton	
	0.94	bone dry tons per 4800000 BTU	
	3450	lbs CO2 per 4800000 BTU	
	719	lbs CO2 per MM Btu	
Compare to Biomass			**Percentage of Biomass**
Coal	**620**	lbs CO2 per MM Btu	**86%**
Petroleum	**561**	lbs CO2 per MM Btu	**78%**
Natural Gas	**385**	lbs CO2 per MM Btu	**54%**

Carbon emissions for Energy Alternative

There are several types of coal that are utilized for electric power in the US, and can be classified by its density of carbon. The CO_2 output per pound of coal is lower for ranks of coal with a lower percentage of carbon, but the energy output per pound of coal is smaller as well. Historically, not just carbon emissions are considered when comparing different types of coal – for instance, sulfur compounds are lower for sub-bituminous coal. Coal plants find it cheaper to use coal with lower sulfur content instead of scrubbing coal with higher sulfur content. In the example, sub-bituminous coal outputs are compared to biomass as a substitute source of electric power. Production and transportation emissions are relatively low, estimated as less than 2% of potential energy produced for coal (Spath et al. 1999).

Life of Wood Products – Other Considerations

At least three factors (not directly dealt with in this report) make wood product life cycle assessments difficult (Profft et al. 2009):

- Wood products may be replaced by new products before the physical end-of-use period, for a variety of reasons.
- Some long-lived products (e.g. laminated beams) have largely unknown life spans.
- Some wood waste is disposed of in landfills, and burned wood waste may or may not be used toward energy production.

Regional demands and mill locations may lead to significantly different allocations to different wood products. This could affect the allocation between long-term and short-term wood products, particularly when choosing between particleboard/medium density fiberboard (MDF) (longer lifespan) vs. pulp/paper products (shorter lifespan). Another effect will be the final disposal of wood products. Products would release carbon more quickly if they were burned for energy or other purposes, as opposed to slower release of carbon for wood products that are disposed of in a landfill (Micales and Skog 1997).

Other Carbon Fluxes

Some of the carbon stores and fluxes within a forest as a result of a thinning are recognized, but not quantified. For example, a mechanical thinning will disturb the forest soil (rutting and compaction), and increased disturbance likely increases carbon flux from the soil. However, the net effect on carbon pools within the soil and soil respiration into the atmosphere, while potentially relatively large, is difficult to measure (Ryu et al. 2009), even though some estimates of carbon soil losses have been estimated in agricultural processes (e.g., Smith et al. 2010). As a result of the difficulty in measuring soil carbon stores and fluxes (and no estimates through FVS) it is not included in the model.

Plot Selection

There are 100 plots from five counties (three FVS regions) that have been selected for simulation in FVS (Table 5). The plots are separated into age groups for simplicity when results are presented.

Table 5. Plot Location Summary.

Region	County	Plot Count	Plots at least 160 years
Eastern Cascade	Wasco	21	4
	Jefferson	22	3
Western Cascade	Linn	17	0
	Douglas	15	4
Blue Mountains	Crook	25	4
	Total Plots	100	15

The approximate coordinates of plots in each county are known (Appendix A). The Forest Service plot database uses “fuzzy coordinates”, but estimated locations are within 1 mile of actual plot centers. Plots were selected to represent a range of the “more common” Landscape Ecology, Modeling, Mapping and Analysis (LEMMA 2010) landscape assignments with stand conditions that represent potential for fuel reduction treatments. No other statement of statistical significance is implied.

Dominant Tree Species for each Plot

Basal area was used to determine the dominant species for each plot (Appendix B). Basal area is the total area occupied by the cross-sections of all trees of a species per unit area. Only species with greater than 10% of total basal area are included for each plot in the tables attached in Appendix B, so the cumulative percentage of species for each plot does not always add up to 100% in the tables. In the analysis, all trees are included in the growth model. For most plots, the primary species are Douglas-fir and ponderosa pine. Several other species were commonly found in these plots, including white fir, incense-cedar, and western hemlock.

Plot Understory Vegetation

Plots that were measured from CVS had vegetation codes (Hall 1998) that were input into FVS. Understory vegetation is divided into four classes:

- Forbs
- Grasses
- Shrubs
- Trees

Vegetation species are reported by the number of plots in which they occur (Appendix C). Understory species were used in estimating the vegetation type when not directly reported in the FIA database, but are considered too bulky for this report. The tables use the following definitions:

- Species listed under "trees" refer to trees that are currently growing at the same height as other understory vegetation (shrubs, forbs, grasses). This does not necessarily indicate the species of the dominant trees within a plot.
- Some of the species are ambiguous – for example, "snowberry" is listed separately from "common snowberry" and "creeping snowberry". The plant definitions for this study are only as precise as the definitions that are available from the source database.
- Only the most common plants were included – if a plant was counted in fewer than 3 plots, it is not included in the summary (but is available).

Table C5 summarizes the number of different plants/ plant groups within each vegetation class that were counted for each plot in four counties.

Carbon Pool Estimates for Plots Prior to Treatment

The Fuels and Fire Extension (FFE) to the Forest Vegetation Simulator (FVS) has integrated reports that estimate forest carbon pools as forest stand growth is simulated. Carbon pool estimates are separated into seven categories:

- Standing live trees
- Belowground live
- Standing dead trees
- Belowground dead
- Downed dead wood (including coarse woody debris)
- Forest floor (including duff)
- Shrubs and herbs

In this analysis, each plot is grown in FVS for 50 years – both the initial carbon pool as well as carbon growth rates are examined and compared to forest volume growth rates to determine site productivity. FVS uses region-specific variants that adjust growth conditions based on regional differences. The Eastern Cascade, Western Cascade, and Blue Mountains variants are used in this study. The plots from each county use the variant recommended by FVS for that county. All plots are simulated and analyzed separately, but only a few of the plots are shown in this report. Plots are chosen from a range of initial conditions. A more detailed explanation of FVS calculations is in Appendix E.

Figure 4 shows carbon estimates for a relatively young stand and Figure 5 for a relatively older stand, assuming no thinning. Note the difference in carbon scales – there is a much lower amount of carbon in the younger stand, but the percentage increase from initial carbon for the younger stand is much higher over the 50-year time frame.

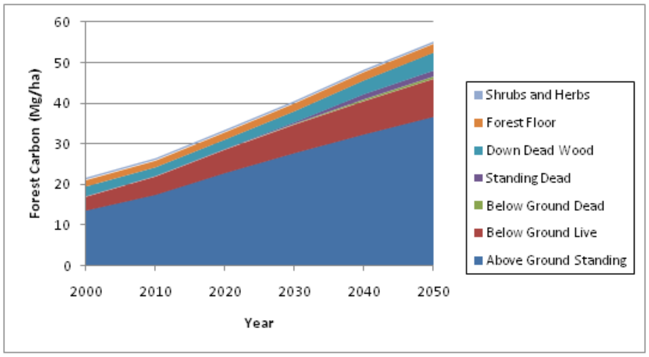


Figure 4. Carbon pool estimates for younger stand.

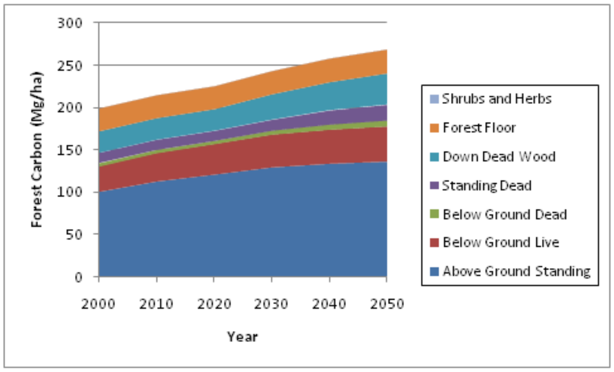


Figure 5. Carbon pool estimates for older stand.

Criteria for Stand Treatments

When thinning the plots, fire hazard was measured using two standard metrics provided by FFE - Torching Index (TI) and Crowning Index (CI). TI is a function of both the vertical stand structure and the height to crown base and CI is a function of crown bulk density (Scott and Reinhardt 2001). The metrics provide the minimum wind speeds required to initiate individual tree torching (TI) and to support a crown fire (CI). The lower the minimum wind speeds the more susceptible the stand is to tree mortality. We use the TI and CI wind speed thresholds used in a recent Oregon/California regional study (Daugherty and Fried 2007). Using these thresholds the stand is a candidate for treatment under one of two conditions:

- TI and CI are both less than 25 mph.
- CI is less than 40 mph, regardless of TI.

Thinning Strategies

In order to determine to test both the sensitivity of forest carbon to thinning intensity and also to include some thinnings that were financially feasible, three different thinning strategies were conducted for each plot.

Light thin

The primary goal of this thinning is to take as few trees as possible while meeting (or exceeding) torching and crowning index criteria. The general approach is to take the smallest trees (0”-6” DBH), and increase by 1” intervals until fuel reduction goals are met. If the TI threshold is met, but the CI threshold was not met, a portion of larger trees (12”-20”) is removed. Several plots could not meet the torching and crowning index criteria. These plots tended to be younger stands with smaller diameters and with relatively low crowns.

“Breakeven” thin

In general, the light thinning does not take enough merchantable timber to pay for the thinning. In order to find a feasible thin, larger trees are taken, but trees less than 20” DBH are targeted. Smallest trees are taken first, but in some plots, some of the smaller trees are left behind (because of the relatively higher cost of removal), and some of the larger trees are taken.

Heavy thin

In this thinning strategy, standing trees are thinned to a relatively low number of trees per acre, leaving only the largest trees. Different tree densities are used for plots from eastern Oregon (40-50 trees per acre) and western Oregon (90-100 trees per acre) (Fitzgerald 2005, Tappeiner et al. 1997).

Stand Treatment Considerations

When selecting a system to treat the stands, three primary criteria are considered in this study.

- Impact to carbon pool within each plot (simulated 50 years from current stand condition).
- Comparison of crowning index and torching index before and after treatment.

- Economics of the treatment (treatment must pay for itself for the breakeven thinning scenario).

Other criteria that are important to consider, but beyond the scope of this study, include

- Laws/regulations and public acceptance of potential treatments, particularly on public lands.
- Safety standards and certifications of contractors hired for potential thinning.

A financial analysis was conducted using the Fuel Reduction Cost Simulator (FRCS-West 2010) and LogCost10.2 (2010), while the FVS FFE extension is used to estimate the Torching Index (TI) and Crowning Index (CI), both of which measure stand conditions and hazards that may contribute to a catastrophic fire. The effectiveness of fuel treatment was assessed based on TI and CI estimates before and after thinning. A detailed analysis of TI and CI at a group level is in Figure F1 and F2.

A financial break-even point (where revenues and cost are equal) depends upon a host of factors, some of which are known, and some of which are estimated. There are many potential fuel treatments available within FRCS, including ground-based operations and cable-based operations. In general, the lowest cost systems are ground-based. Ground-based thinning operations can be separated into whole-tree and cut-to-length operations, both which have advantages and disadvantages. One harvesting system is used for plots on more gentle terrain (slopes ≤ 30%), and a slightly different system is used for plots with steeper terrain (slopes >30%).

For more gentle slopes, the following whole-tree system is used:

- Drive-to-tree feller/buncher
- Grapple skidder
- Processing/chipping/loading at the landing
- Truck and trailer transport to nearest mill/plant.

For steeper slopes, the drive-to tree feller/buncher is replaced with a swing-boom feller/buncher, which is more stable on steeper slopes, but is limited to the length of the boom and may lead to less flexibility in tree removal. For longer skidding distances, the cut-to-length system (CTL) becomes less expensive than whole-tree skidding due to the higher load carrying capability of forwarders. CTL systems can also have lower mobilization costs, important in small, low volume treatment units, because fewer pieces of equipment are transported between harvest units.

Example Plot

The following example details a plot that is assessed with the model created for this study. In order to fully describe the analysis for each plot, one of the plots (21561) from Jefferson County (eastern Oregon) was chosen. Plot parameters are known (Table 6), and the analysis for this plot follows.

Table 6. Summary information for the example plot (metric, English units).

Plot Attributes	
Species	Ponderosa pine, Douglas-fir
Age	72 yrs avg for dominant/codominant trees
	Uneven aged stand ranging from seedlings to >200 years
Basal Area	152 ft^2/acre (35 m^2/hectare)
Height	69 ft (21 m) avg for dominant/codominant
Initial Wood Volume	3390 ft^3/acre (237 m^3/hectare)
Initial C Store (live aboveground)	28.7 tons/acre (64.4 MgC/hectare)
Initial C Store (total)	49.3 tons/acre (110.4 MgC/hectare)

Torching and Crowning Index

Initial FVS estimates for TI (38 mph) and CI (32 mph) indicate that the stand is a candidate for fuel treatment, because CI < 40 mph. The slope is gentle for this particular stand (<5%), so a drive-to-tree feller/buncher is chosen as part of the whole-tree mechanical thinning system

Silvicultural Prescription and Carbon Effects

- The plot initially has 380 trees/acre. Similar to the other plots, this plot has three implemented scenarios for thinnings (light, heavy, and break-even); this example has three scenarios to illustrate general relationships between economics and fuel reduction for most plots. Silvicultural prescriptions implemented for this particular stand includes:

Trampling smaller fuel sources to reduce fuel loading as part of the drive-to-tree feller/buncher operation. Including trampling as an option in FVS reduces fuel depth by a factor of 0.75. This affects fire intensity (increases TI and CI) but does not affect fuel consumption in a potential fire. (Reinhardt et al. 2003).

“Light” Thinning
(208 trees/acre remaining – TI=38, CI=54):

- Removing 100% of trees less than 10 in. DBH
- The resistance to crown fire is improved and resistance to individual tree torching is unchanged.

“Break-even” Thinning
(164 trees/acre remaining – TI =40, CI=54):

- Removing 100% of trees less than 7 in. DBH
- Removing 20% of trees 7-20 in. DBH
- Corresponds to a removal of fewer smaller trees and a higher number of larger trees while marginally meeting fuel reduction goals.

“Heavy” Thinning
(46 trees/acre remaining – TI=39, CI=66):

- Removing 100% of trees less than 12 in. DBH
- Removing 30% of trees 12-16 in. DBH
- Removing 10% of trees 16-20 in. DBH
- Leaves the stand in a relatively park-like condition, with little understory and only a few of the largest trees remaining. This stand structure might simulate some eastern Oregon historical structures (Fitzgerald 2005). Both resistance to torching and crowning have significantly increased.

All thinnings reduce forest carbon pools, and heavier thinnings lead to less carbon on-site than lighter thinnings, both immediately and over the 50-year simulated period. Plot-level estimates of carbon pools, carbon transfer to wood products, and potential avoided carbon emission by biomass burning for energy (compared to a coal alternative) are compared (Figure 6). Twenty percent of the slash created from harvested trees is left in the stand following a thinning. The live wood volume in Figure 6 is total live green volume/unit area (m^3/hectare), and is included as both a reference and as an additional metric to manually check for any gross discrepancies in the growth and yield model.

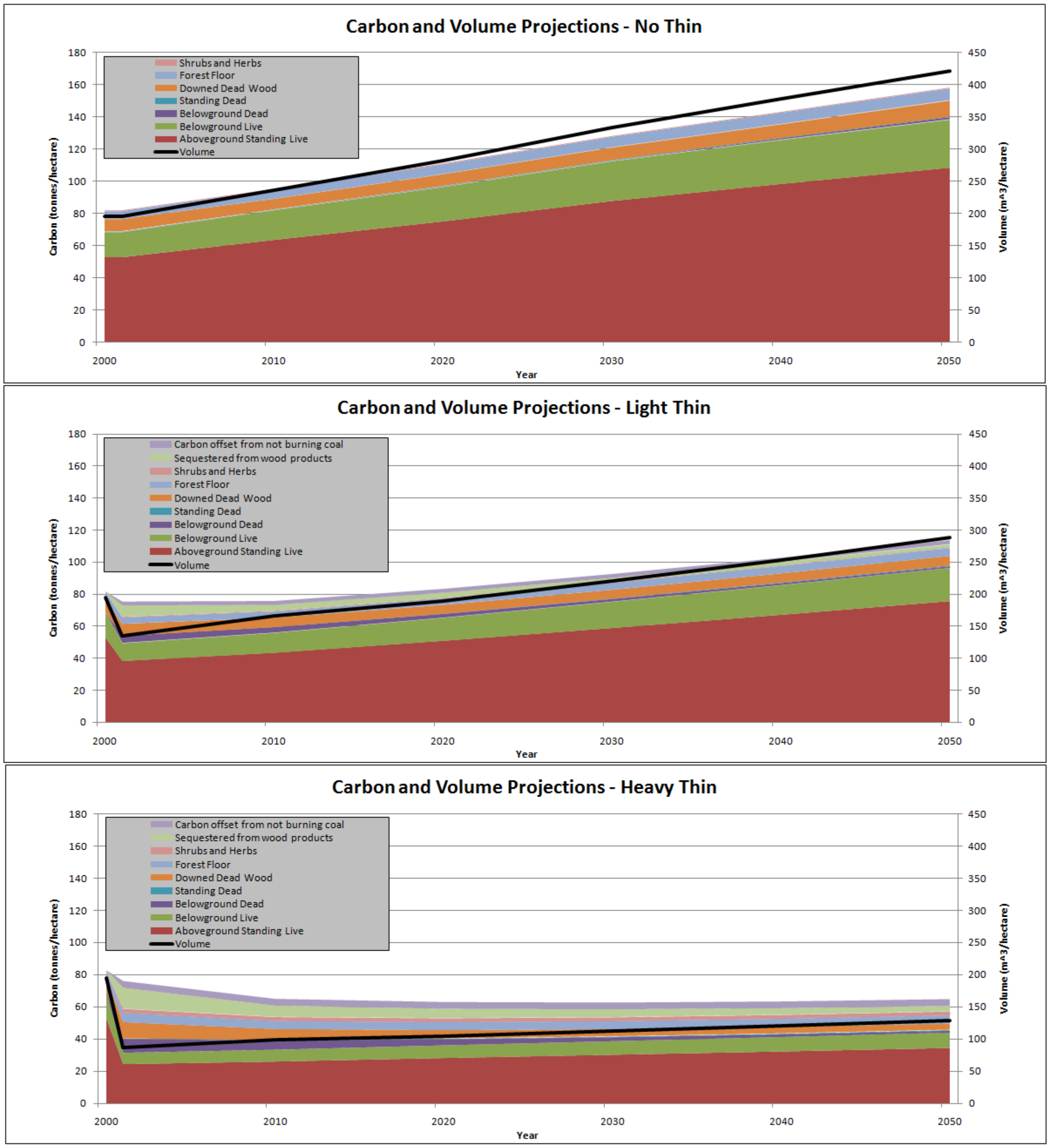


Figure 6. Simulation of carbon pools for the forest stand – No Thin (top), Light Thin (middle) and Heavy Thin (bottom).
All carbon components reference the left axis. Only standing green tree volume (Volume) references the right axis.

Harvesting System

The harvesting system for this stand includes five major pieces of equipment and two types of transportation vehicles:

- Drive-to-tree feller/buncher – Mechanically falls each tree and lays trees into groups (bunches) for efficient handling.
- Grapple skidder – Grabs whole tree bunches and drags trees to a roadside landing.
- Processor – Located at the roadside landing. Delimbs and bucks trees into merchantable lengths.
- Chipper – Located at the roadside landing. Chips small whole trees (< 6" DBH) and tops and branches from larger trees directly into a chip van.
- Loader – Located at the roadside landing. Maneuvers small whole trees and residues into the chipper and logs into log trucks.
- Truck with Chip Van – Transports chips from landing to destination. Capacity for vans in this example is 110 cubic yards.
- Truck with Log Trailer – Transports logs from landing to mill.

This is a thinning system that removes whole trees to the landing. There is a potential for residual stand damage that must be considered in both harvest planning and operations.

A Cut-to-Length (CTL) system could be used at a comparatively lower cost for thinning at longer skidding distances when compared to a whole-tree system (Kellogg et al. 2010), but a CTL system was not included in the final economic analysis, since average skidding distance in this report is assumed to be 500 feet (also assumed by Dempster el al. 2008).

Costs

Costs are separated into four components:

- Planning/administration costs – includes timber sale preparation and administration. Sales preparation and administration estimates for nonfederal (Nall 2010, Sessions et al. 2000) and national forest land (TSPIRS 2001, adjusted for inflation) are estimated in Table 7. The federal land administrative costs are not included in the "breakeven" analysis, and administrative costs vary widely from sale to sale, according to federal requirements, including compliance with the National Environmental Policy Act (NEPA) and other federal laws (e.g., USFS 2010). In general, federal land sales preparation and administration costs are higher compared to private land. The estimate used in the example is a general example only, and should not be used to estimate actual costs.
- Setup costs – includes one-time move-in cost to an area, moving costs from landing to landing, sales preparation cost, and road maintenance costs (Table 8).
- Cost from field to truck, including felling/bunching, skidding, chipping, processing, and loading (Table 9).
- Cost to transport each wood product (Table 10).

The planning/administration costs are shown, but are not included in the final analysis.

Table 7. Sales preparation and administration costs associated with the three thinning scenarios.

Preparation/Administration Costs	light	heavy	break-even	units
Sales Preparation/Admin (Non-federal)	42	26	32	$/mbf
	141	**143**	**142**	$/acre
Sales Preparation/Admin (Federal)	173	173	173	$/mbf
	581	**964**	**765**	$/acre

Table 8. Estimated equipment setup costs for the three thinning scenarios.

Setup Costs	light	heavy	break-even	units
Move-in Cost (5 equipment pieces)	33	33	33	$/day
1 acre average/day	33	33	33	$/acre
Moving Costs (Landing to Landing)	75	75	75	$/acre
Road Maintenance Costs	33	59	37	$/acre
Total Setup	**141**	**168**	**145**	**$/acre**

Table 9. Estimated costs from field to truck for the three thinning scenarios.

Cost from Field to Truck	light	heavy	break-even	units
Felling/bunching	225	441	133	$/acre
Skidding	210	455	252	$/acre
Chipping whole trees	26	51	13	$/acre
Chipping loose residues	14	40	32	$/acre
Processing Logs	162	392	183	$/acre
Loading Logs	71	192	130	$/acre
Total to Truck	**708**	**1571**	**743**	$/acre

Table 10. Estimated truck transport cost for the three thinning scenarios.

Cost from Truck to Final Destination	light	heavy	break-even	units
Chip Trucking (Transport + Delays)	16	16	16	$/green ton
	133	**213**	**127**	$/acre
Log Trucking (Transport + Delays)	48	48	48	$/mbf
	134	**267**	**167**	$/acre
Total Truck to Final Destination	**266**	**480**	**295**	$/acre

Wood Products

The volume and mix of wood products derived from the thinning is critical when calculating total revenue from the stand. The mix of trees removed from the plot is separated by diameter class (Table 11). FVS simulated the total volume (ft^3) per plot and merchantable volume (Mbf) in order to estimate timber value. A 16 ft scaling rule (Scribner) was used for plots in eastern Oregon, and the midrange diameter was used to estimate the Mbf:cf ratio for each diameter class (e.g., 7” was used for 6”- 8” sawtimber) which was found with a conversion chart (Mann and Lysons 1972 – Fig 4).

Table 11. Allocation of thinned trees into wood products.

Products	light	heavy	break-even	units
Saw timber				
6"-8"	1.77	3.53	1.41	CCF/acre
8"-10"	2.78	5.56	2.23	CCF/acre
10"-12"	1.01	2.03	0.81	CCF/acre
12"-16"	1.01	1.52	2.54	CCF/acre
16"-20"	0	0.45	0.5	CCF/acre
Total Saw Timber	**2.78**	**5.57**	**3.51**	mbf/acre
Chips	**8.1**	**13.0**	**8.2**	tons/acre

Sawlog prices are estimated using the Oregon Department of Forestry Log Price Information (Oregon Dept. of Forestry 2010). The biomass market returns significantly lower prices than the pulp market, but it is assumed that the biomass chip quality does not meet pulp chip standards (Table 12).

Table 12. Estimated delivered harvested wood product prices.

Market	price	units
Sawlogs	285	$/mbf
Chips	60	$/BDT

Overall Cost/Revenue Analysis

For this particular scenario with the given assumptions, there is **a net profit of $72/acre** for the “breakeven thin” scenario on non-federal lands (Table 13). Both the “light” and “heavy” thin result in treatment costs exceeding revenues given the initial assumptions. These three different thinning scenarios demonstrate that increasing gross revenue or total volume does not necessarily improve net revenue, and depending on original stand structure, may significantly increase harvesting costs. In order for this thinning to not incur financial losses on federal lands, a relatively high proportion of high-value stems and a relatively low proportion of low-value stems would need to be thinned.

Table 13. Total costs and revenues, using non-federal costs - per acre basis.

Revenue	light	heavy	break-even	units
Sawlogs	794	1421	1011	$/acre
Biomass	243	390	243	$/acre
Gross Revenue	1037	1811	1254	$/acre
Minus Costs	1116	2219	1182	$/acre
Net Revenue	**-79**	**-409**	**72**	$/acre

The amount of carbon in the stand after 50 years compared to the initial carbon pool varies with the intensity of the thinning and the type of thinning. Using the initial amount of live aboveground carbon and total aboveground carbon as a benchmark, the net effect on carbon after 50 years (excluding wood products or avoided carbon emissions) can be estimated (Table 14).

Table 14. Simulated carbon outputs, excluding harvested wood products.

Carbon Pool	Treatment	Year 0	Year 50
Total Carbon (MgC/ha)	No Thin	83.2	158.7
	Light Thinning	71.2	99.2
	Heavy Thinning	59.8	70.6
Aboveground Live Standing Carbon (MgC/ha)	No Thin	53.6	105.6
	Light Thinning	35.8	59.1
	Heavy Thinning	29.8	43.6

Analysis

Other plots in this analysis were analyzed in a similar way to the example plot, with the primary difference in prescriptions between plots being the number and class of trees removed. The analysis methodology was the same between plots and regions.

Several harvesting assumptions are made – average skidding distance is 500 ft for all plots, which is highly variable, and directly affects cost. There are 16-foot Scribner scaling rules used for plots east of the Cascades and 32- foot Scribner scaling rules for plots west of the Cascades. Different prices per Mbf are used for both eastern and western Oregon, and a 20% premium is assumed for plots in western Oregon, due to differences in scaling rules. However, the price will also differ between regions at any given time due to species differences, market conditions, and other factors.

Biomass price is assumed to be $60/ton throughout the region – biomass price fluctuates, and the profitability will be greatly impacted by the market price. Lower prices would make it much more difficult for the landowner to "breakeven". To reduce cost, the landowner may take the approach of only removing the most "profitable" biomass (e.g., biomass near a roadside, biomass in areas with shorter transport distance to final destination).

Detailed thinning prescriptions and plot-level ranges of carbon estimates were made for each plot. The general trends (minimum, maximum, and average) of carbon estimates for all plots are split into two regions (eastern Oregon and western Oregon), and are included in Appendix D. Detailed Tables are included (Appendix F).

Results

For most plots, forest carbon pools (both live aboveground and total) are significantly reduced when comparing thin to no thin. After simulating growth in the stands for 50 years the average difference in net carbon balance between unthinned and thinned plots for the three age groups ranged between 73.5 – 103.4 MgC/ha in Eastern Oregon to 121.8 – 128.6 MgC/ha in Western Oregon.

Carbon levels of thinned plots do not reach the carbon levels of unthinned plots within a simulated timeframe of 50 years, even after including carbon transferred to harvested wood products and the avoided emissions from using biomass instead of fossil fuels for energy. See Table 15 for an overall carbon budget by thinning scenario and region. See Appendix F for a group-level summary of carbon stores (Table F1), relative carbon flux over time (Table F2), fuel loading measurement (Table F3), and plot-level comparison of carbon stores (Table F4).

- Older stands, which tended to have lower carbon flux annually (as a percentage of initial carbon stores), did not "recapture" carbon as quickly as younger stands following a light thinning.
- All stands had lower carbon flux into the stand from the atmosphere following a heavy thinning, when compared to a lighter thinning or no thinning.
- Stands in eastern Oregon tended to have less carbon flux when compared to stands in western Oregon.

Regarding wood products:

- Larger trees had a greater percentage of carbon transferred to wood products with a relatively longer half-life for carbon. Smaller trees had a greater percentage of carbon transferred to products with a shorter carbon half-life (such as paper or burning for biomass).
- Carbon dioxide output per unit energy produced is higher for biomass stand-alone facilities compared to fossil fuels, but the gap is closed somewhat if energy is used for heating instead. This study ignores other pollutants (such as SO_x emissions), that are higher for coal when compared to biomass (NREL 2000).

Financial analysis:

- With the additional goal of no financial loss, a higher percentage of larger, more valuable trees must be thinned in order to cover the cost of removing smaller, less valuable trees.
- Heavy thins were often unprofitable, and depended on the assumptions in the economic model as well as original stand structure. There are many fuel reduction treatments that were not included, such as mastication or slash piling. These alternative techniques might reduce costs by leaving smaller stems in the field, but would also affect carbon impacts and potentially affect crowning and torching indices.

The estimated carbon budget for these plots (based on carbon stores and fluxes - Figure 2) is shown (Table 15).

Table 15. Carbon budgets for thinning and no-thinning scenarios (all age groups combined; time interval = 50 years; units are MgC/ha).

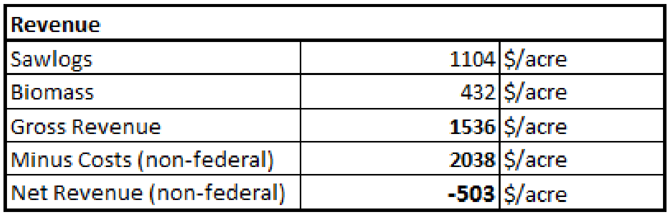
Region	Thinning Scenario	Net Change on Site	Equipment Emissions	Paper products	Lumber products	Paper/ lumber disposal (in landfills)	Emissions from biomass burning for energy	Offset from not burning fossil fuels	Net Carbon balance	Average Annual Sequestration Rate MgC/ha/year	Difference between Thin and No Thin
Eastern Oregon	No Thinning	90.67	0.00	0.00	0.00	0.00	0.00	0.00	90.67	1.81	0.00
	Light Thinning	14.53	-0.59	0.00	2.08	4.05	-7.48	4.56	17.15	0.34	-73.52
	"Break-even" Thinning	-15.81	-1.05	0.00	4.52	8.80	-10.56	6.44	-7.66	-0.15	-98.33
	Heavy Thinning	-27.54	-1.62	0.00	7.47	14.54	-14.35	8.76	-12.75	-0.25	-103.42
Western Oregon	No Thinning	81.97	0.00	0.00	0.00	0.00	0.00	0.00	81.97	1.64	0.00
	Light Thinning	-40.22	-0.48	0.00	1.20	2.10	-6.21	3.79	-39.82	-0.80	-121.79
	"Break-even" Thinning	-53.62	-1.30	0.00	7.06	9.88	-10.85	6.62	-42.21	-0.84	-124.18
	Heavy Thinning	-58.31	-2.26	0.00	8.64	11.08	-14.88	9.08	-46.65	-0.93	-128.62

*All Units in MgC/ha except for annual sequestration rate

Financial Sensitivity

Some of the plots dominated by smaller stems could not be thinned without financial loss, given the assumptions for these plots. For instance, Plot 26510 (Wasco County) has a relatively high density (538 trees per acre), but quadratic mean diameter (QMD) is 7”, and the largest trees are 10” DBH. Varying the thin affects the financial loss per acre, even for nonfederal land. For instance, a thinning to 200 trees per acre using initial assumptions results in a net loss of -$503/acre (Table 16).

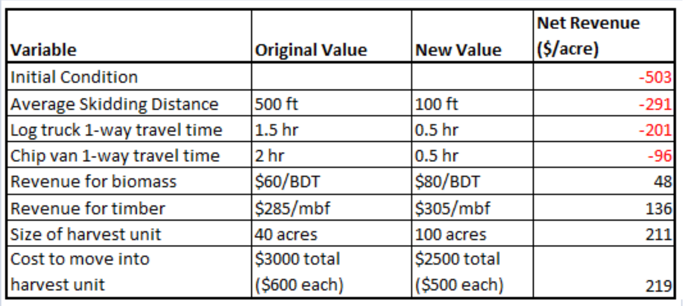
Table 16. Initial financial loss for Plot 26510.



Revenue		
Sawlogs	1104	$/acre
Biomass	432	$/acre
Gross Revenue	**1536**	$/acre
Minus Costs (non-federal)	**2038**	$/acre
Net Revenue (non-federal)	**-503**	$/acre

However, given different assumptions, it is feasible for this thinning to break even or turn a small profit for the landowner. Financial feasibility is improved if (1) the harvested wood is closer to the landing, (2) the transport distance to a mill/plant is shorter, (3) higher wood product market prices exist and (4) harvest units are larger and closer together. Incremental changes to these four factors can together dramatically affect cost or revenue for this plot (Table 17).

Table 17. Favorable conditions allow the landowner to financially break even. Net revenue reflects cumulative changes of assumptions. For example: reducing skidding distance improves net revenue from -$503/ac to -$291/ac and simultaneously shortening log truck travel time improves net revenue to -$201/ac.



Variable	**Original Value**	**New Value**	**Net Revenue ($/acre)**
Initial Condition			-503
Average Skidding Distance	500 ft	100 ft	-291
Log truck 1-way travel time	1.5 hr	0.5 hr	-201
Chip van 1-way travel time	2 hr	0.5 hr	-96
Revenue for biomass	$60/BDT	$80/BDT	48
Revenue for timber	$285/mbf	$305/mbf	136
Size of harvest unit	40 acres	100 acres	211
Cost to move into harvest unit	$3000 total ($600 each)	$2500 total ($500 each)	219

If the landowner’s decision is largely focused on profit or loss, these factors must be carefully considered. In order to decrease skidding costs, the landowner may decide to harvest only near the roadside, or may only harvest on flatter terrain. It is also more likely that regions nearest mills and plants and existing road infrastructure would be thinned, due to decreased transport distance. Activities in marginal stands may be postponed until periods of higher markets or treatment in marginal stands combined with more profitable stands to create a breakeven situation. Depending on objectives, the landowner may leave the plot untouched, or may apply another management prescription.

Other socio-political factors could affect landowner decisions in both short and long term. Subsidies for forest biomass (e.g., $10/green ton subsidy – HB2210 Oregon 2007) can increase revenues and allow thinning to become more economically viable. Price premiums for carbon from public or private sources may also affect a landowner’s decision. Uncertainty associated with these potential sources of revenue would be considered by the landowner in long-term planning.

Potential Alternative Management for Younger Stands

For many of the younger stands (especially stands with relatively low QMD and relatively high trees/acre), it was not possible to simultaneously thin the stand to the desired TI and CI while maintaining a profit, given the harvesting and market assumptions. For these stands, there are several alternatives that may be considered for fuel reduction:

- Alternative silvicultural prescriptions, such as prescribed fire, could be used to reduce fuels while initiating some level of stand mortality and raising base to the live crown.
- Only the least expensive areas could be thinned – for example, treating only the areas nearest roadside, areas with flatter terrain, or areas nearest the mill would reduce cost while still implementing some level of fuel reduction.
- Leave the stand “as is”, and potentially treat the stand at a later time after the stand naturally reaches a different stand structure.

Other Carbon Fluxes

The thinning analysis in this paper addresses the effect on carbon pools from removing selected trees from a stand in an effort to improve forest resilience to fire. The reference scenario is the "no treatment" scenario. For some owners, this may be appropriate, but for others, alternative reference scenarios may be more useful. For example, do longer rotations with one or more thinnings sequester more carbon than shorter rotations with no thinnings? In this case a short rotation with no thinning becomes the reference scenario. Or does uneven-aged management sequester more carbon than even-aged management? In this case even-aged management becomes the reference scenario.

We also do not address carbon fluxes from precommercial thinning (PCT) where trees are currently thinned to waste as compared to the options of planting lower tree densities or delaying PCT until the trees increase commercial value.

Lastly, we not address the effect on carbon pools from utilization of forest residues following a commercial harvest operation where residues are piled at roadside as part of the normal harvesting operations and later burned to reduce fuel hazard, release area for new plantations, and to reduce habitat for rodents. In this case slash burning and short term release would be the reference scenario as compared to residue utilization for energy substitution.

Next Steps

Future analysis could

- Simulate wildfire and prescribed fire over long timeframes in stands with and without thinning in order to more fully understand the effects of wildfire on carbon pools.
- Broaden carbon accounting to include the substitution of wood products for building materials such as concrete, steel, and aluminum.
- Simulate the effects on carbon pools and fire after either natural seedling in-growth or planting in the understory.

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Appendix A. Coordinates of Plots for each County

Figure A1. Wasco County plot locations.

Figure A2. Jefferson County plot locations.

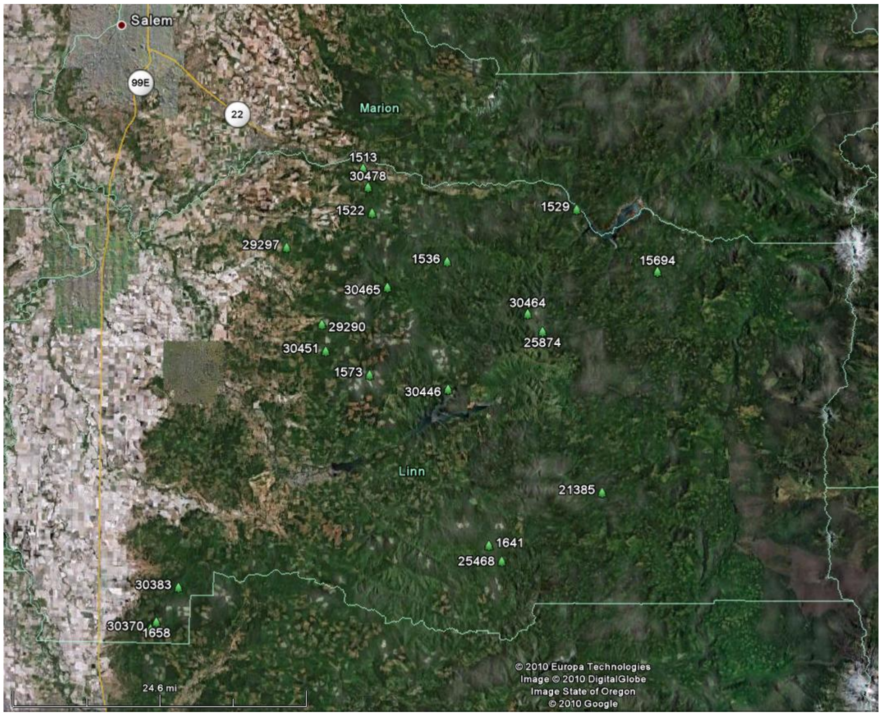


Figure A3. Linn County plot locations.

Figure A4. Douglas County plot locations.

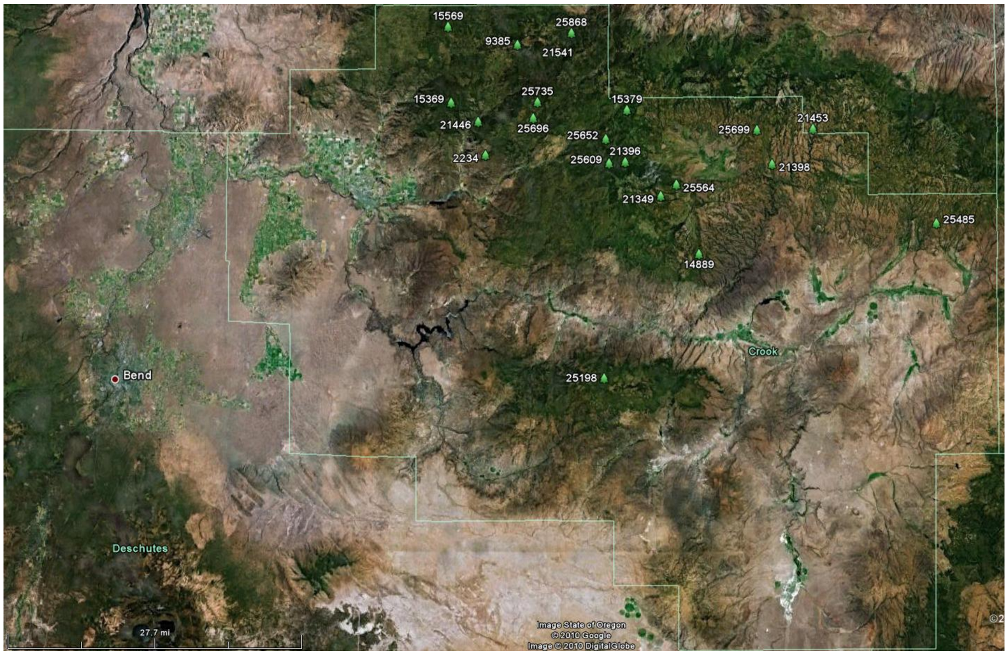


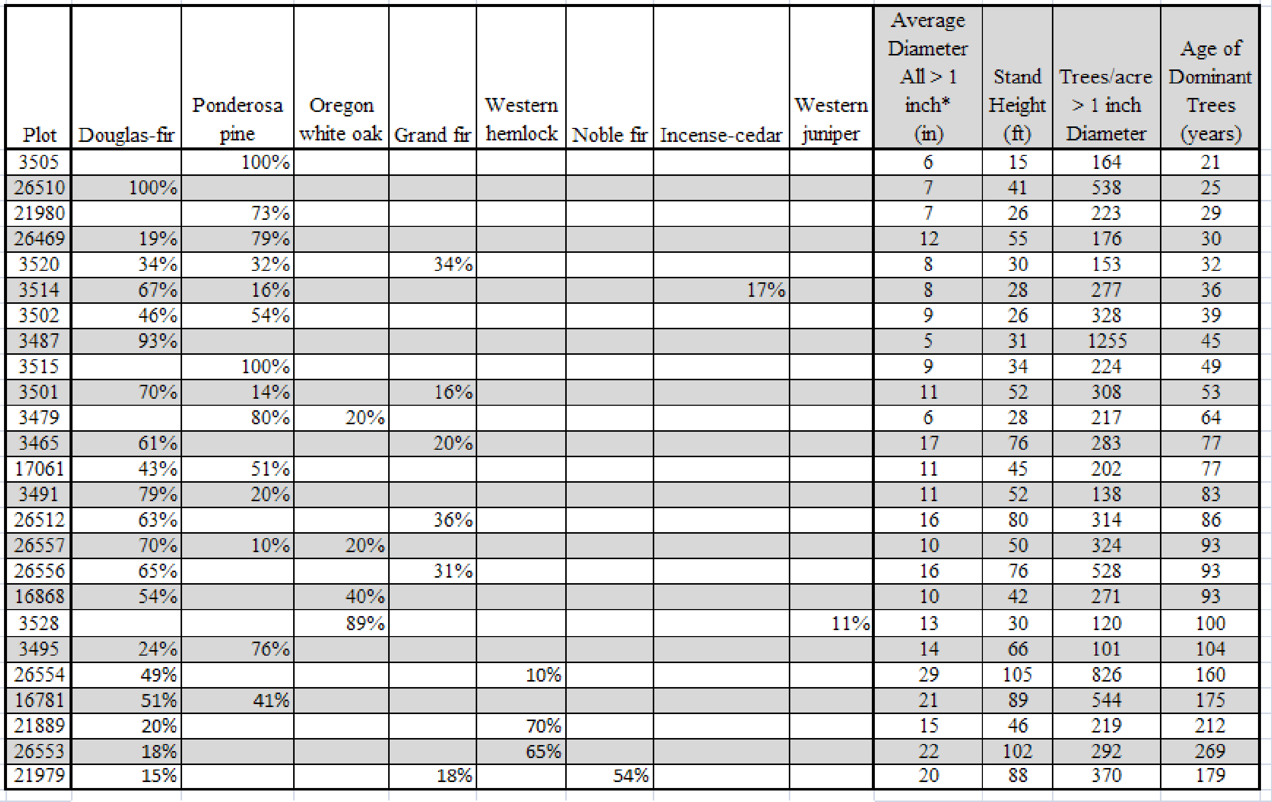
Figure A5. Crook County plot locations.

Oregon State University

College of Forestry

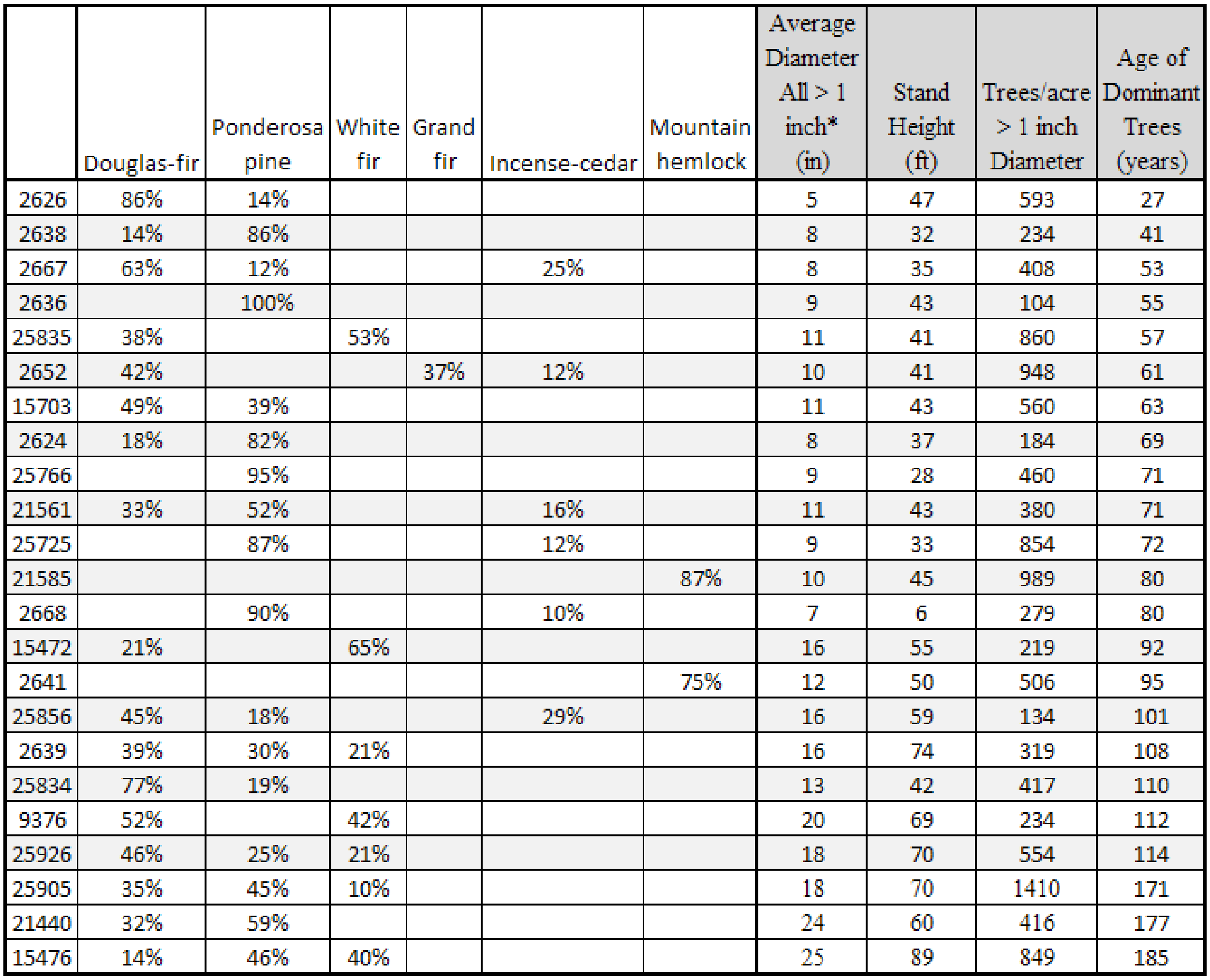
Appendix B. Stand Level Characteristics for each Plot, by County

Table B1. Wasco County - dominant species (percentage of total basal area) and associated tree data.



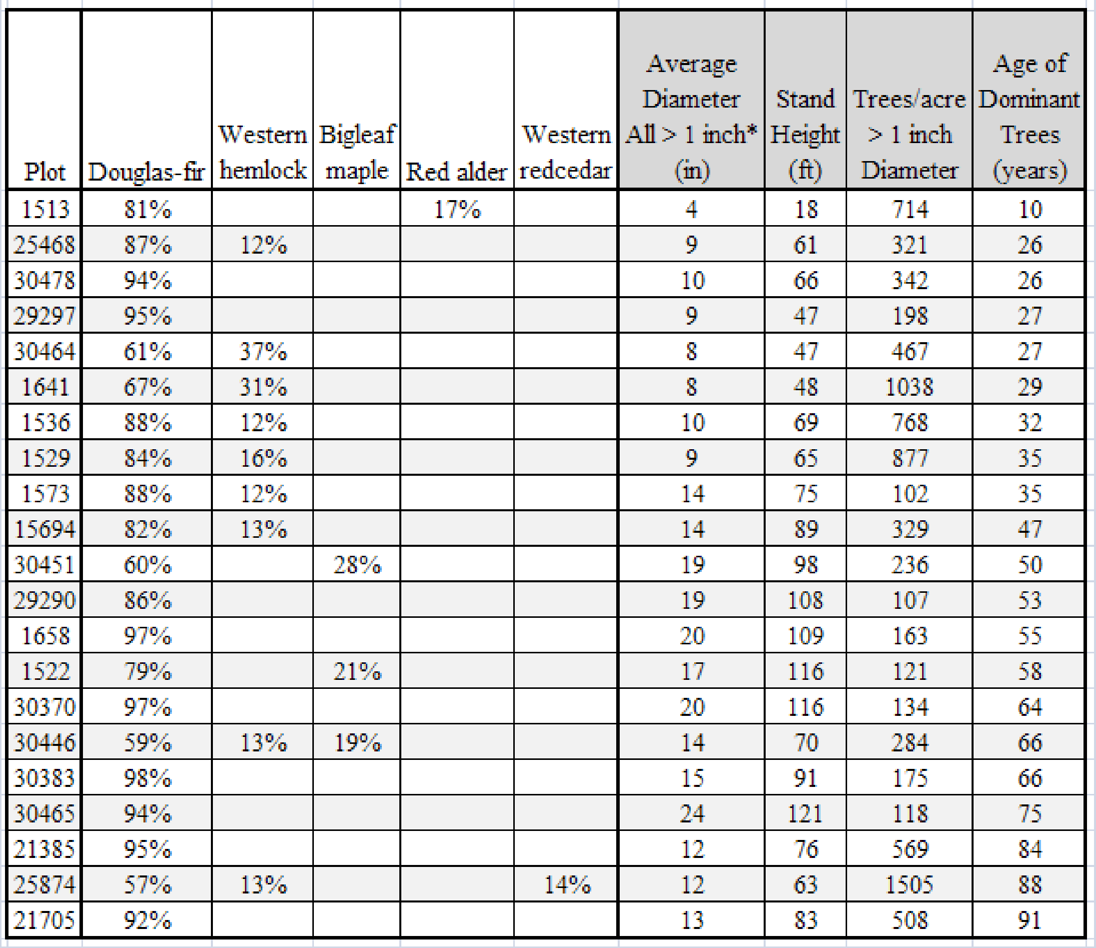
Plot	Douglas-fir	Ponderosa pine	Oregon white oak	Grand fir	Western hemlock	Noble fir	Incense-cedar	Western juniper	Average Diameter All > 1 inch* (in)	Stand Height (ft)	Trees/acre > 1 inch Diameter	Age of Dominant Trees (years)
3505		100%							6	15	164	21
26510	100%								7	41	538	25
21980		73%							7	26	223	29
26469	19%	79%							12	55	176	30
3520	34%	32%		34%					8	30	153	32
3514	67%	16%					17%		8	28	277	36
3502	46%	54%							9	26	328	39
3487	93%								5	31	1255	45
3515		100%							9	34	224	49
3501	70%	14%		16%					11	52	308	53
3479		80%	20%						6	28	217	64
3465	61%			20%					17	76	283	77
17061	43%	51%							11	45	202	77
3491	79%	20%							11	52	138	83
26512	63%			36%					16	80	314	86
26557	70%	10%	20%						10	50	324	93
26556	65%			31%					16	76	528	93
16868	54%		40%						10	42	271	93
3528			89%					11%	13	30	120	100
3495	24%	76%							14	66	101	104
26554	49%				10%				29	105	826	160
16781	51%	41%							21	89	544	175
21889	20%				70%				15	46	219	212
26553	18%				65%				22	102	292	269
21979	15%			18%		54%			20	88	370	179

Table B2. Jefferson County - dominant species (percentage of total basal area) and associated tree data.



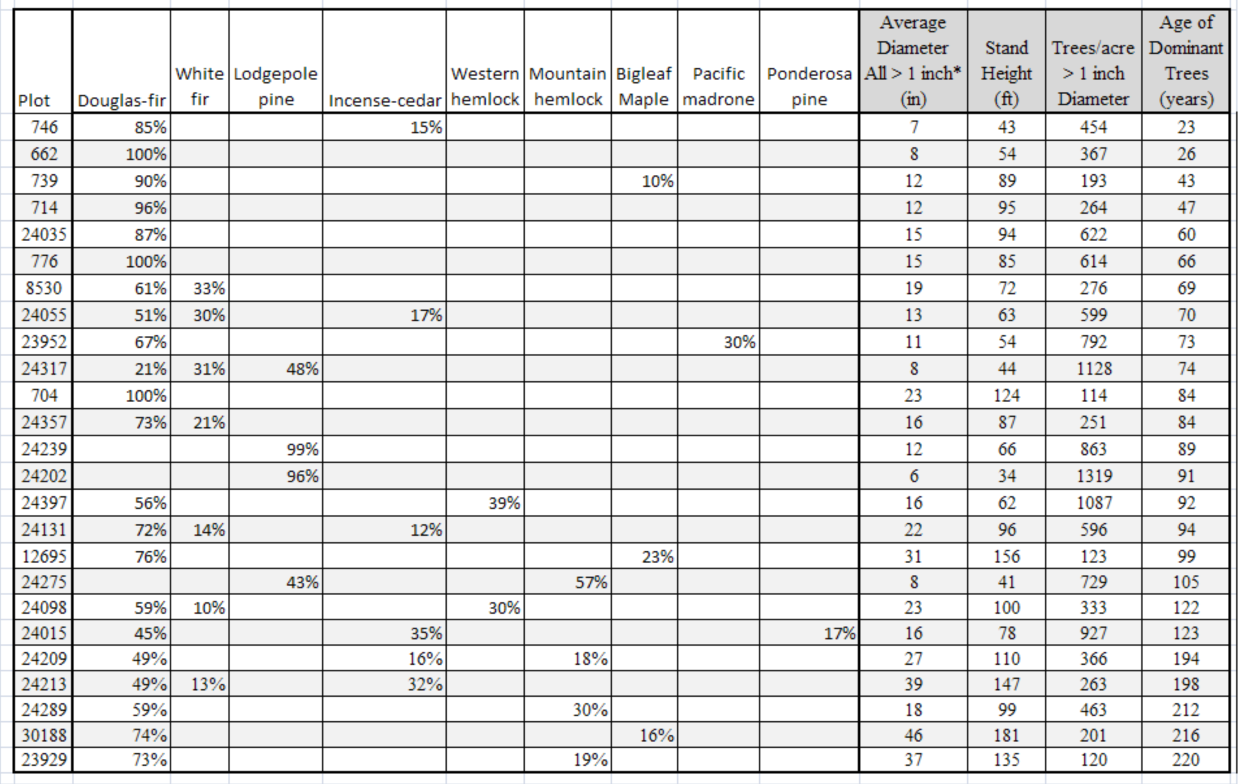
	Douglas-fir	Ponderosa pine	White fir	Grand fir	Incense-cedar	Mountain hemlock	Average Diameter All > 1 inch* (in)	Stand Height (ft)	Trees/acre > 1 inch Diameter	Age of Dominant Trees (years)
2626	86%	14%					5	47	593	27
2638	14%	86%					8	32	234	41
2667	63%	12%			25%		8	35	408	53
2636		100%					9	43	104	55
25835	38%		53%				11	41	860	57
2652	42%			37%	12%		10	41	948	61
15703	49%	39%					11	43	560	63
2624	18%	82%					8	37	184	69
25766		95%					9	28	460	71
21561	33%	52%			16%		11	43	380	71
25725		87%			12%		9	33	854	72
21585						87%	10	45	989	80
2668		90%			10%		7	6	279	80
15472	21%		65%				16	55	219	92
2641						75%	12	50	506	95
25856	45%	18%			29%		16	59	134	101
2639	39%	30%	21%				16	74	319	108
25834	77%	19%					13	42	417	110
9376	52%		42%				20	69	234	112
25926	46%	25%	21%				18	70	554	114
25905	35%	45%	10%				18	70	1410	171
21440	32%	59%					24	60	416	177
15476	14%	46%	40%				25	89	849	185

Table B3. Linn County - dominant species (percentage of total basal area) and associated tree data.



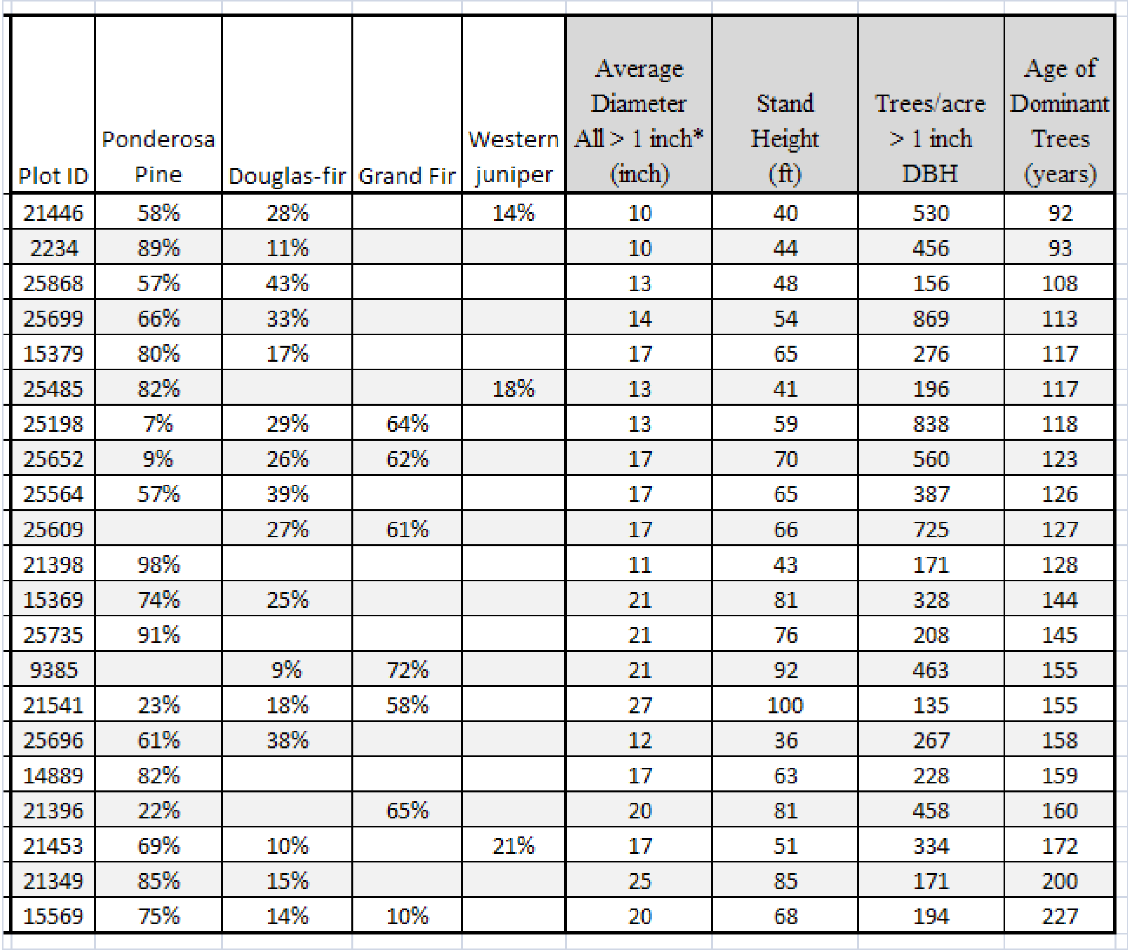
Plot	Douglas-fir	Western hemlock	Bigleaf maple	Red alder	Western redcedar	Average Diameter All > 1 inch* (in)	Stand Height (ft)	Trees/acre > 1 inch Diameter	Age of Dominant Trees (years)
1513	81%			17%		4	18	714	10
25468	87%	12%				9	61	321	26
30478	94%					10	66	342	26
29297	95%					9	47	198	27
30464	61%	37%				8	47	467	27
1641	67%	31%				8	48	1038	29
1536	88%	12%				10	69	768	32
1529	84%	16%				9	65	877	35
1573	88%	12%				14	75	102	35
15694	82%	13%				14	89	329	47
30451	60%		28%			19	98	236	50
29290	86%					19	108	107	53
1658	97%					20	109	163	55
1522	79%		21%			17	116	121	58
30370	97%					20	116	134	64
30446	59%	13%	19%			14	70	284	66
30383	98%					15	91	175	66
30465	94%					24	121	118	75
21385	95%					12	76	569	84
25874	57%	13%			14%	12	63	1505	88
21705	92%					13	83	508	91

Table B4. Douglas County - dominant species (percentage of total basal area) and associated tree data.



Plot	Douglas-fir	White fir	Lodgepole pine	Incense-cedar	Western hemlock	Mountain hemlock	Bigleaf Maple	Pacific madrone	Ponderosa pine	Average Diameter All > 1 inch* (in)	Stand Height (ft)	Trees/acre > 1 inch Diameter	Age of Dominant Trees (years)
746	85%			15%						7	43	454	23
662	100%									8	54	367	26
739	90%						10%			12	89	193	43
714	96%									12	95	264	47
24035	87%									15	94	622	60
776	100%									15	85	614	66
8530	61%	33%								19	72	276	69
24055	51%	30%		17%						13	63	599	70
23952	67%							30%		11	54	792	73
24317	21%	31%	48%							8	44	1128	74
704	100%									23	124	114	84
24357	73%	21%								16	87	251	84
24239			99%							12	66	863	89
24202			96%							6	34	1319	91
24397	56%				39%					16	62	1087	92
24131	72%	14%		12%						22	96	596	94
12695	76%						23%			31	156	123	99
24275			43%			57%				8	41	729	105
24098	59%	10%			30%					23	100	333	122
24015	45%			35%					17%	16	78	927	123
24209	49%			16%		18%				27	110	366	194
24213	49%	13%		32%						39	147	263	198
24289	59%					30%				18	99	463	212
30188	74%						16%			46	181	201	216
23929	73%					19%				37	135	120	220

Table B5. Crook County - dominant species (percentage of total basal area) and associated tree data.



Plot ID	Ponderosa Pine	Douglas-fir	Grand Fir	Western juniper	Average Diameter All > 1 inch* (inch)	Stand Height (ft)	Trees/acre > 1 inch DBH	Age of Dominant Trees (years)
21446	58%	28%		14%	10	40	530	92
2234	89%	11%			10	44	456	93
25868	57%	43%			13	48	156	108
25699	66%	33%			14	54	869	113
15379	80%	17%			17	65	276	117
25485	82%			18%	13	41	196	117
25198	7%	29%	64%		13	59	838	118
25652	9%	26%	62%		17	70	560	123
25564	57%	39%			17	65	387	126
25609		27%	61%		17	66	725	127
21398	98%				11	43	171	128
15369	74%	25%			21	81	328	144
25735	91%				21	76	208	145
9385		9%	72%		21	92	463	155
21541	23%	18%	58%		27	100	135	155
25696	61%	38%			12	36	267	158
14889	82%				17	63	228	159
21396	22%		65%		20	81	458	160
21453	69%	10%		21%	17	51	334	172
21349	85%	15%			25	85	171	200
15569	75%	14%	10%		20	68	194	227

Appendix C. Understory Vegetation by County

Table C1. Most common understory vegetation for Wasco County plots.

Category	Common name	Plots
Shrubs	dwarf rose	17
	common snowberry	15
	Cascade barberry	12
	snowbrush ceanothus	10
	antelope bitterbrush	9
	greenleaf manzanita	9
	oceanspray	9
	Saskatoon serviceberry	9
	creeping snowberry	8
	giant chinquapin	8
	pipsissewa	8
	California blackberry	7
	snowberry	6
	willow	6
	California hazelnut	5
	Oregon boxleaf	5
	vine maple	5
	creeping barberry	3
	honeysuckle	3
	plum	3
	thinleaf huckleberry	3
Trees	ponderosa pine	7
	Douglas-fir	6
	Oregon white oak	3

Category	Common name	Plots
Forbs	common yarrow	8
	blue windflower	7
	bride's bonnet	7
	fragrant bedstraw	7
	largeleaf sandwort	7
	lupine	7
	woodland strawberry	7
	Columbian windflower	6
	Pacific trillium	6
	sweetcicely	6
	Virginia strawberry	6
	houndstongue hawkweed	5
	western brackenfern	5
	American trailplant	4
	arrowleaf balsamroot	4
	twinflower	4
	western rattlesnake plantain	4
	white hawkweed	4
	broadleaf starflower	3
	leafy pea	3
	liverleaf wintergreen	3
	sidebells wintergreen	3
	sweet after death	3
Grasses	Idaho fescue	12
	California brome	9
	cheatgrass	8
	sedge	8
	bluebunch wheatgrass	5
	Grass, annual	5
	western fescue	5
	Geyer's sedge	4
	Kentucky bluegrass	4
	pinegrass	4
	squirreltail	4
	Columbia brome	3

Table C2. Most common understory vegetation for Jefferson County plots.

Category	Common name	Plots
Shrubs	greenleaf manzanita	13
	snowbrush ceanothus	12
	antelope bitterbrush	12
	Saskatoon serviceberry	12
	pipsissewa	12
	common snowberry	10
	dwarf rose	8
	giant chinquapin	7
	prostrate ceanothus	5
	Cascade barberry	3
	hollyleaved barberry	3
Trees	incense-cedar	5
	ponderosa pine	5
	Douglas-fir	4

Category	Common name	Plots
Forbs	Virginia strawberry	10
	tailcup lupine	9
	white hawkweed	9
	houndstongue hawkweed	8
	arrowleaf balsamroot	7
	common yarrow	7
	Forb, dicot	7
	western brackenfern	6
	Nevada pea	5
	broadleaf starflower	4
	bull thistle	4
	glaucous beardtongue	3
	largeleaf sandwort	3
Grasses	Idaho fescue	9
	long-stolon sedge	8
	squirreltail	7
	California brome	5
	western fescue	5
	cheatgrass	4
	pinegrass	4
	bluebunch wheatgrass	3
	Grass, perennial	3
	Ross' sedge	3
	western needlegrass	3
	Wheeler bluegrass	3

Table C3. Most common understory vegetation for Linn County plots.

Category	Common name	Plots
Shrubs	vine maple	18
	California blackberry	17
	Cascade barberry	16
	salal	16
	red huckleberry	14
	dwarf rose	9
	California hazelnut	9
	Pacific rhododendron	8
	pipsissewa	7
	oceanspray	7
	creeping snowberry	4
	oval-leaf blueberry	4
	common snowberry	3
	willow	3
	salmonberry	3
	thinleaf huckleberry	3
Trees	western hemlock	9
	Douglas-fir	5
	grand fir	4

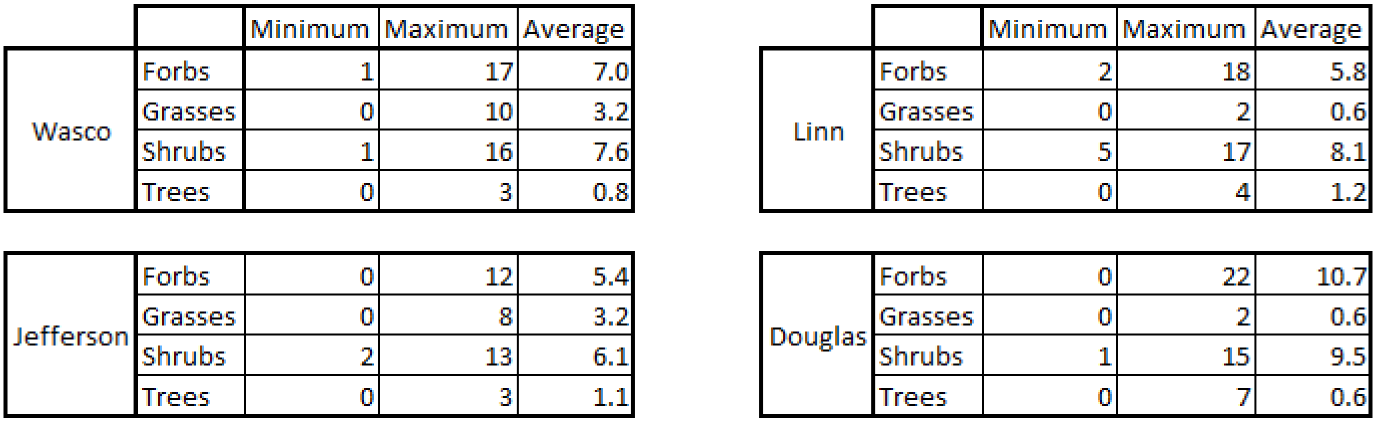
Category	Common name	Plots
Forbs	western swordfern	19
	western brackenfern	10
	common beargrass	8
	white insideout flower	8
	Forb, dicot	6
	fragrant bedstraw	5
	twinflower	5
	British Columbia wildginger	4
	broadleaf starflower	4
	redwood sorrel	4
	Siberian springbeauty	4
	common whipplea	3
	sweet after death	3
	western rattlesnake plantain	3
	white hawkweed	3
Grasses	sedge	6

Table C4. Most common understory vegetation for Douglas County plots.

Category	Common name	Plots
Shrubs	dwarf rose	15
	California blackberry	15
	Cascade barberry	12
	pipsissewa	10
	oceanspray	9
	salal	9
	vine maple	7
	red huckleberry	7
	California hazelnut	7
	honeysuckle	6
	creeping snowberry	6
	Saskatoon serviceberry	5
	thimbleberry	5
	Pacific rhododendron	5
	greenleaf manzanita	4
	Oregon boxleaf	4
	pinemat manzanita	4
	whitebark raspberry	4
	snow raspberry	4
	grouse whortleberry	3
	common snowberry	3
	giant chinquapin	3
	hollyleaved barberry	3
	Himalayan blackberry	3
	Pacific poison oak	3
Trees	Douglas-fir	4

Category	Common name	Plots
Forbs	western swordfern	12
	western brackenfern	11
	woodland strawberry	11
	common whipplea	10
	darkwoods violet	9
	western rattlesnake plantain	9
	broadleaf starflower	8
	Columbian windflower	8
	twinflower	8
	white hawkweed	8
	American trailplant	7
	drops of gold	7
	Forb, dicot	7
	Pacific trillium	6
	purple sweetroot	6
	stickywilly	6
	sidebells wintergreen	5
	starry false lily of the vally	5
	sweet after death	5
	bride's bonnet	4
	pioneer violet	4
	white insideout flower	4
	broadleaf arnica	3
	common beargrass	3
	fragrant bedstraw	3
Grasses	Idaho fescue	7
	long-stolon sedge	3

Table C5. Summary of understory vegetation variety for plots at the county level.



		Minimum	Maximum	Average
Wasco	Forbs	1	17	7.0
	Grasses	0	10	3.2
	Shrubs	1	16	7.6
	Trees	0	3	0.8

		Minimum	Maximum	Average
Linn	Forbs	2	18	5.8
	Grasses	0	2	0.6
	Shrubs	5	17	8.1
	Trees	0	4	1.2

Jefferson	Forbs	0	12	5.4
	Grasses	0	8	3.2
	Shrubs	2	13	6.1
	Trees	0	3	1.1

Douglas	Forbs	0	22	10.7
	Grasses	0	2	0.6
	Shrubs	1	15	9.5
	Trees	0	7	0.6

Appendix D. Detailed Carbon Simulations, Grouped by Age, Region, and Thinning

For the general analysis, it is simpler to separate the plots into groups and to look at general trends. Plots are separated into two regions – eastern Oregon and western Oregon. For each region, stands are grouped into three age classes:

- Young (less than 60 years old in western Oregon, less than 70 years old in eastern Oregon)
- Medium (60-120 years old in western Oregon, 70-120 years old in eastern Oregon)
- Old (greater than 120 years old in western or eastern Oregon).

Stands are further groups into four scenarios for each age group: (1) no treatment, (2) light thinning, (3) break-even (economically) thinning, and (4) heavy thinning, or park-like tree density (in an analysis similar to the example provided in the report).

Table D1. Classification of plots into two regions, six groups, and twenty-four scenarios.

Region	Group	Scenario	Region	Group	Scenario
Western Oregon	Young (< 60 years)	no treatment	Eastern Oregon	Young (< 70 years)	no treatment
		light thinning			light thinning
		break-even thinning			break-even thinning
		heavy thinning			heavy thinning
	Medium (60-120 years)	no treatment		Medium (70-120 years)	no treatment
		light thinning			light thinning
		break-even thinning			break-even thinning
		heavy thinning			heavy thinning
	Old (> 120 years)	no treatment		Old (> 120 years)	no treatment
		light thinning			light thinning
		break-even thinning			break-even thinning
		heavy thinning			heavy thinning

From the analysis of these particular plots, several patterns emerge:

- The relative amount of carbon and total volume after 50 years is highest in the "No Treatment" scenario for each of the six groups.
- The relative amount of carbon and total volume after 50 years is lowest in the "Heavy Thinning" scenario for each of the six groups including considerations of downstream wood utilization in forest products and bioenergy.
- The average relative amount of carbon and total volume is higher in all scenarios after 50 years for the "Light Thinning" scenario, when compared to the "Break-even Thinning" and the "Heavy Thinning" scenario.
- Younger stands – Tended to show the highest rate of carbon accumulation, but not necessarily the greatest absolute accumulation of carbon.
- Older stands – These stands tended to be thinned heavily for dense stands, which tended to have significant understory that led to fuel ladders. Largest trees were preserved, and the approach was to develop a "park-like" scenario with most fuels in the understory removed (all stems <12" diameter and a relatively low residual density of stems 12-20" diameter).

- Eastern Oregon vs. western Oregon – The plots in western Oregon tended to have higher amounts of initial carbon, and higher rates of carbon and volume accumulation. This relationship was observed for all scenarios.

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This set of plots does not necessarily indicate carbon levels at a regional level, and a spatial analysis should be conducted before making broader conclusions based on these simulations.

Guide to Reading Graph Legends

Average Live Carbon. Simulates aboveground carbon store of all live standing trees and shrubs/herbs. There is one solid line that represents average simulated carbon for all plots in the given scenario (MgC/ha).

Average Total Carbon. Simulates sum of forest carbon pools estimated by FVS and allometric equations. There is one solid line that represents average simulated carbon for all plots in the given scenario (MgC/ha).

Average Carbon Offset from not Burning Coal. When burning biomass for energy instead of coal, the carbon emissions for biomass replaces the carbon emissions for coal. This bar includes the estimated "avoided" carbon emissions for each thinning scenario when burning biomass for energy instead of coal (MgC/ha).

Average Carbon stored in Wood Products- This is the estimated carbon transferred and stored in harvested wood products for each thinning scenario (MgC/ha).

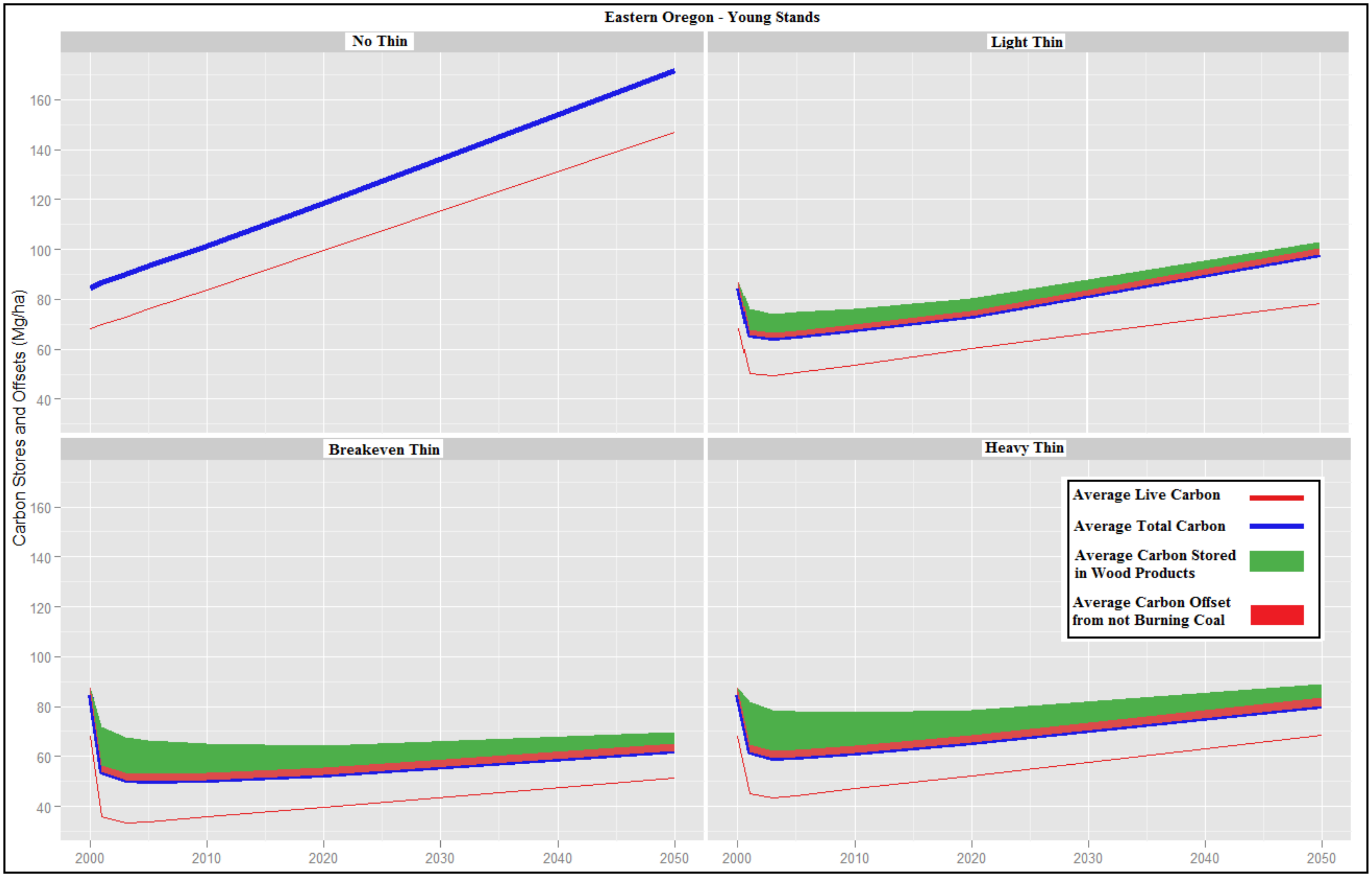


Figure D1. Eastern Oregon – young stands. Simulation of carbon pools for the forest stand over a 50 year period. Biomass for energy is not included in wood product sequestration – it is assumed utilized within the first year.

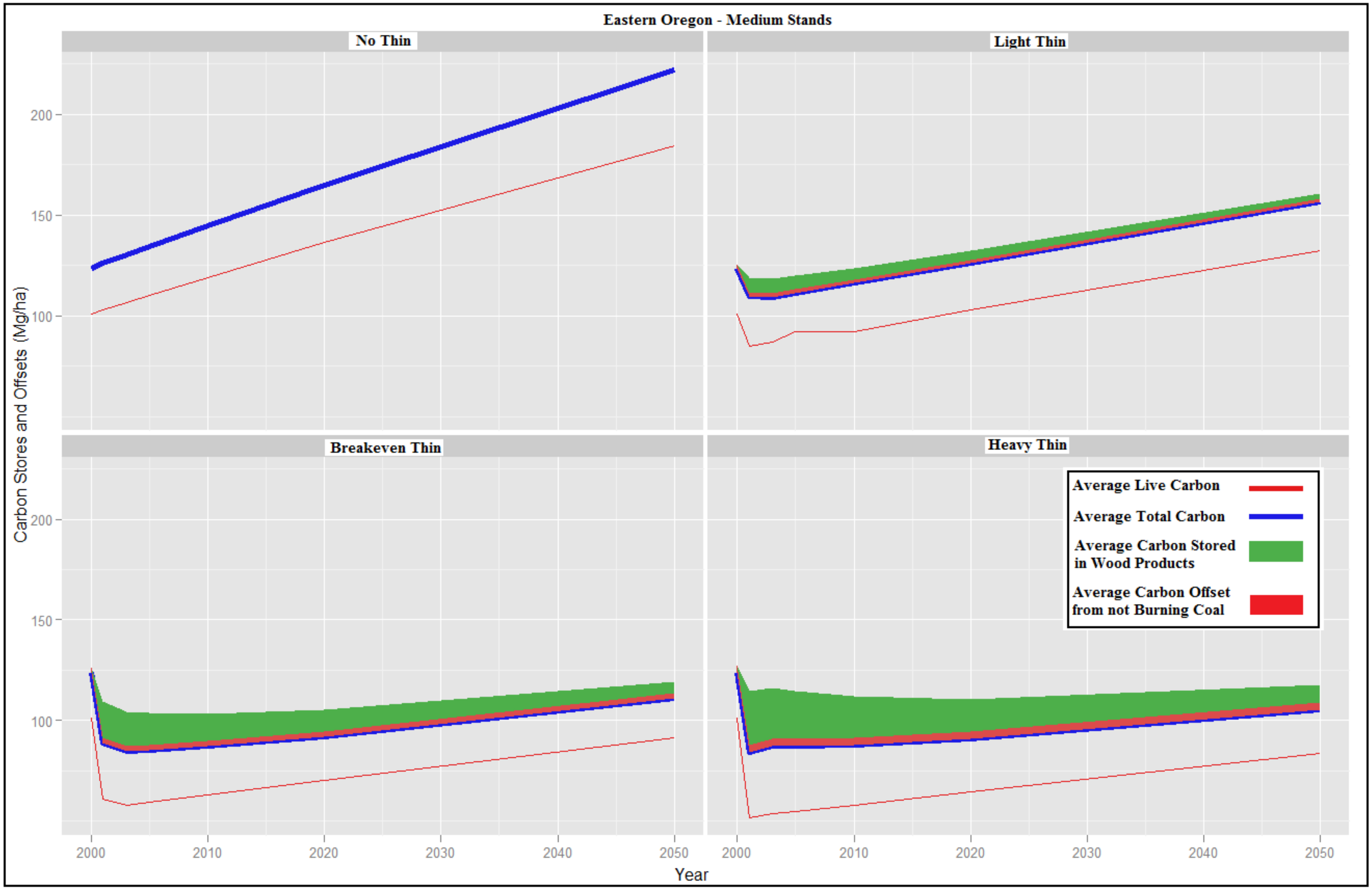


Figure D2. Eastern Oregon – medium stands. Simulation of carbon pools for the forest stand over a 50 year period. Biomass for energy is not included in wood product sequestration – it is assumed utilized within the first year.

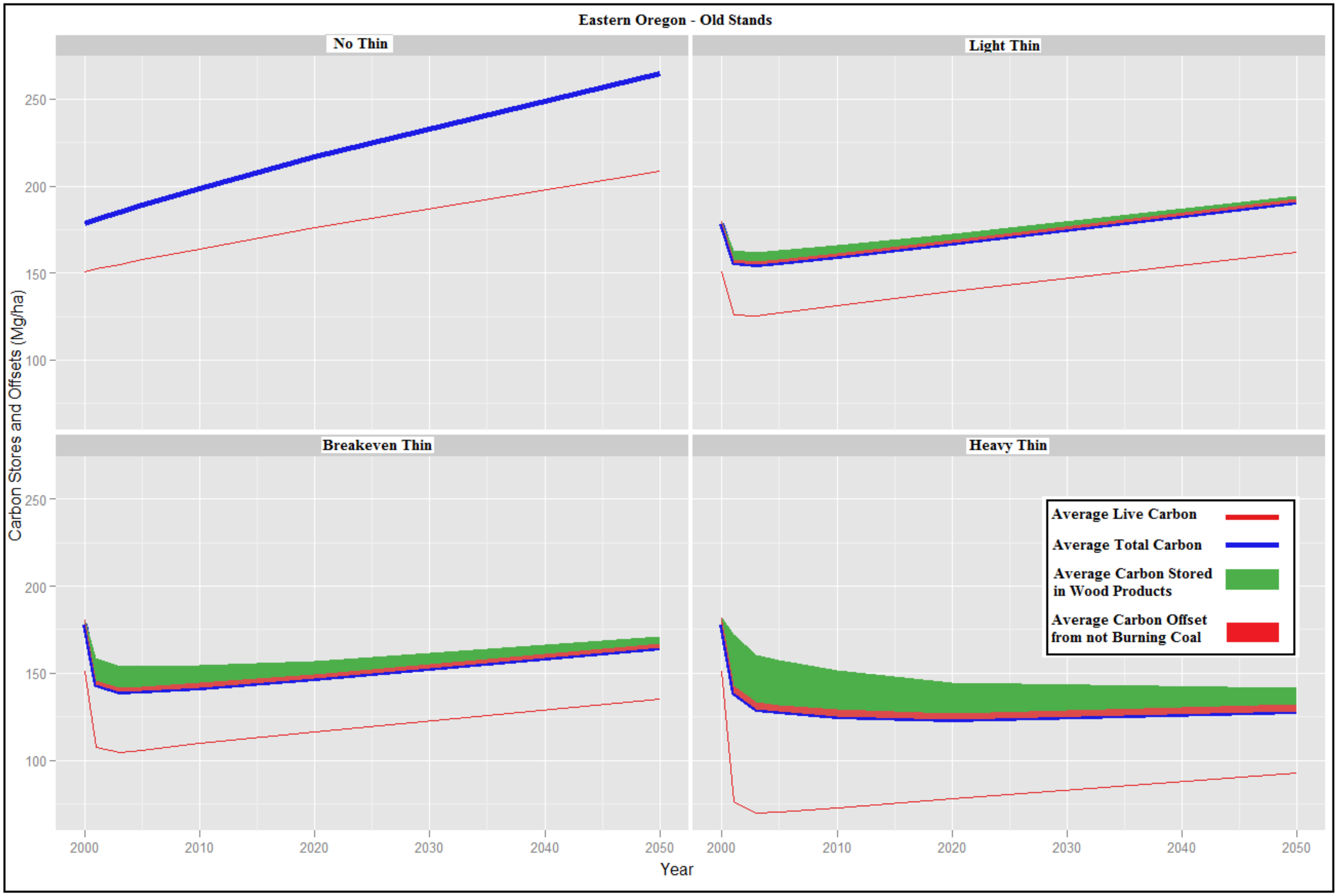


Figure D3. Eastern Oregon – old stands. Simulation of carbon pools for the forest stand over a 50 year period. Biomass for energy is not included in wood product sequestration – it is assumed utilized within the first year.

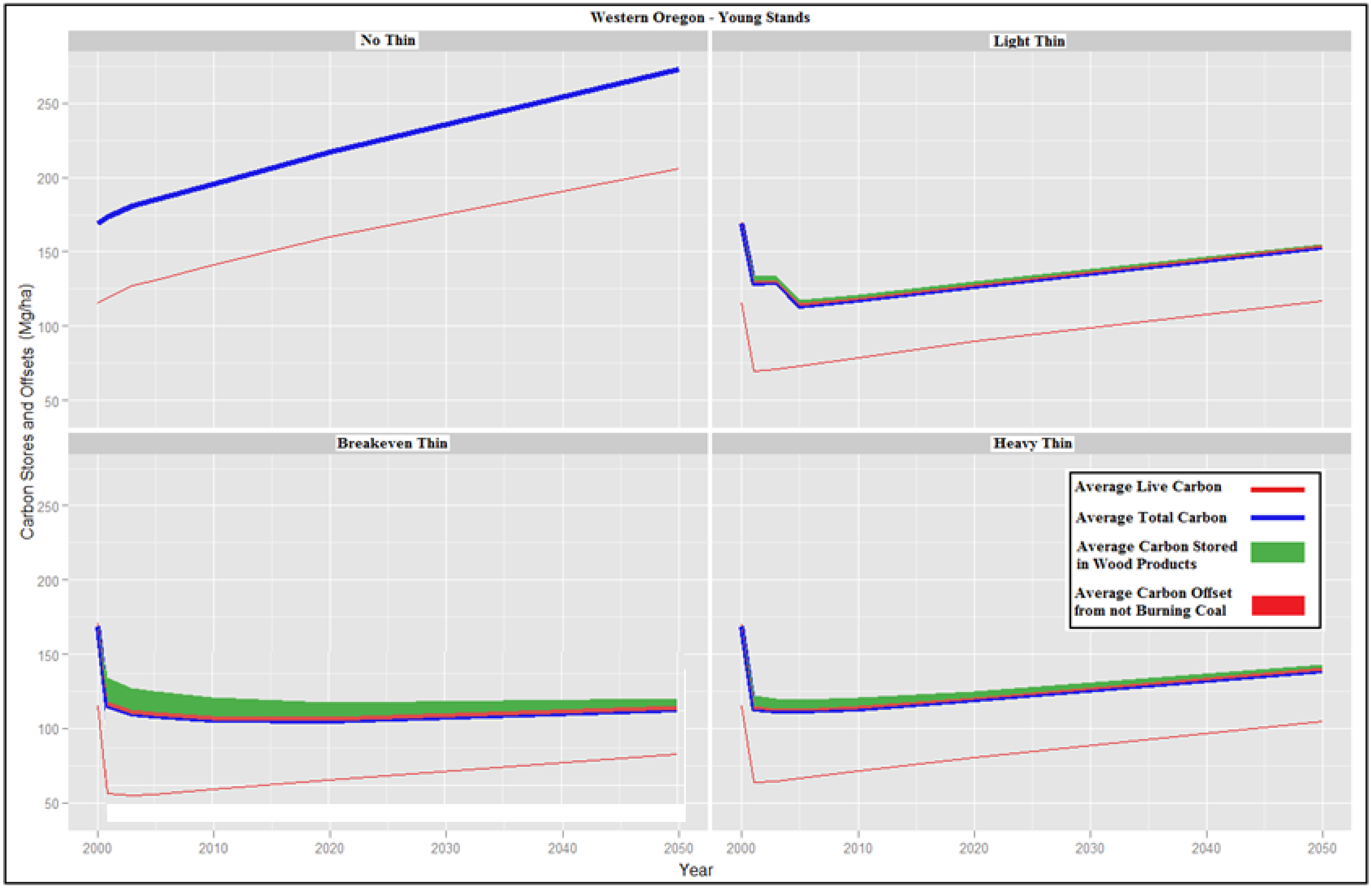


Figure D4. Western Oregon – young stands. Simulation of carbon pools for the forest stand over a 50 year period. Biomass for energy is not included in wood product sequestration – it is assumed utilized within the first year.

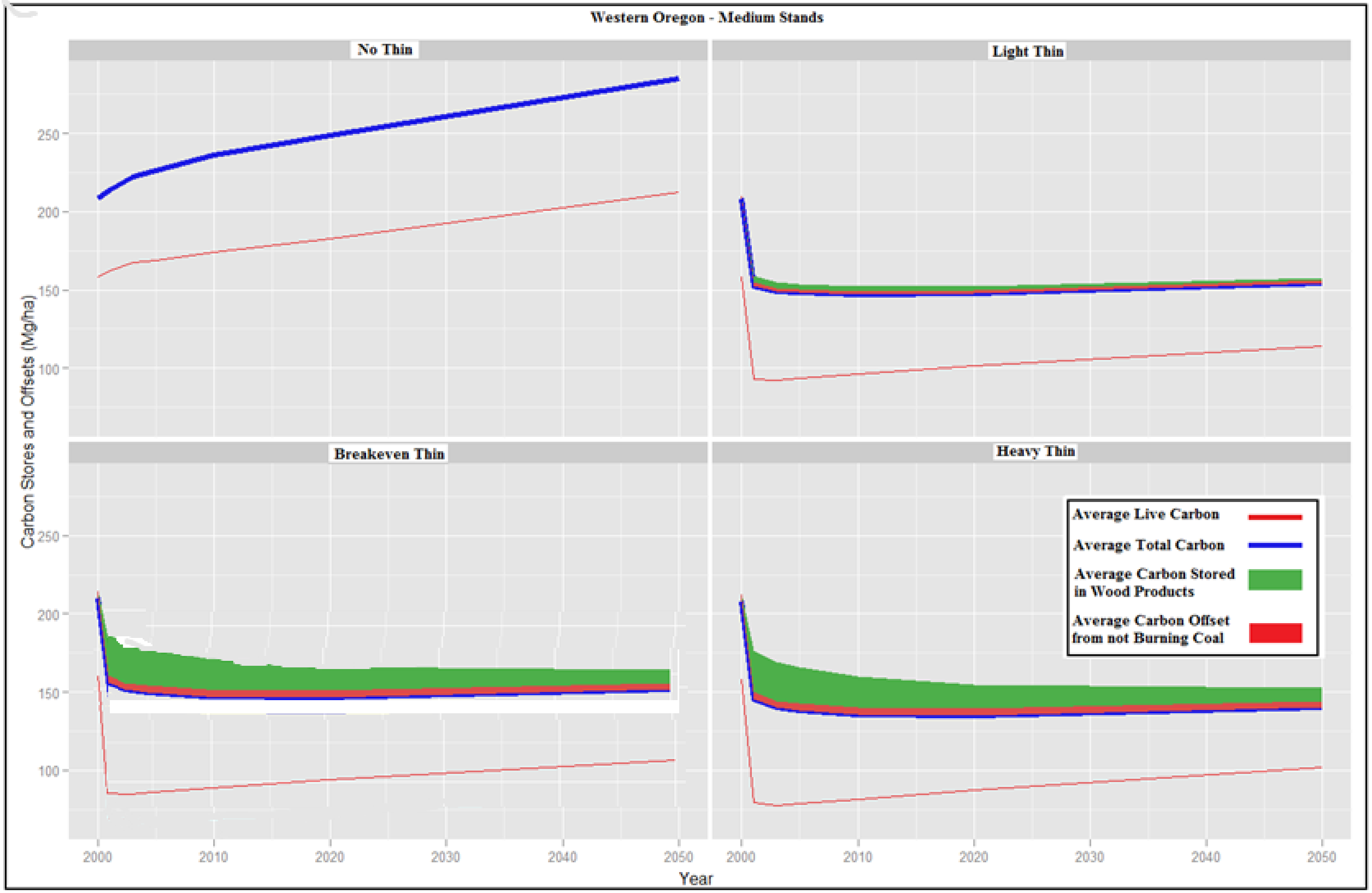


Figure D5. Western Oregon – medium stands. Simulation of carbon pools for the forest stand over a 50 year period. Biomass for energy is not included in wood product sequestration – it is assumed utilized within the first year.

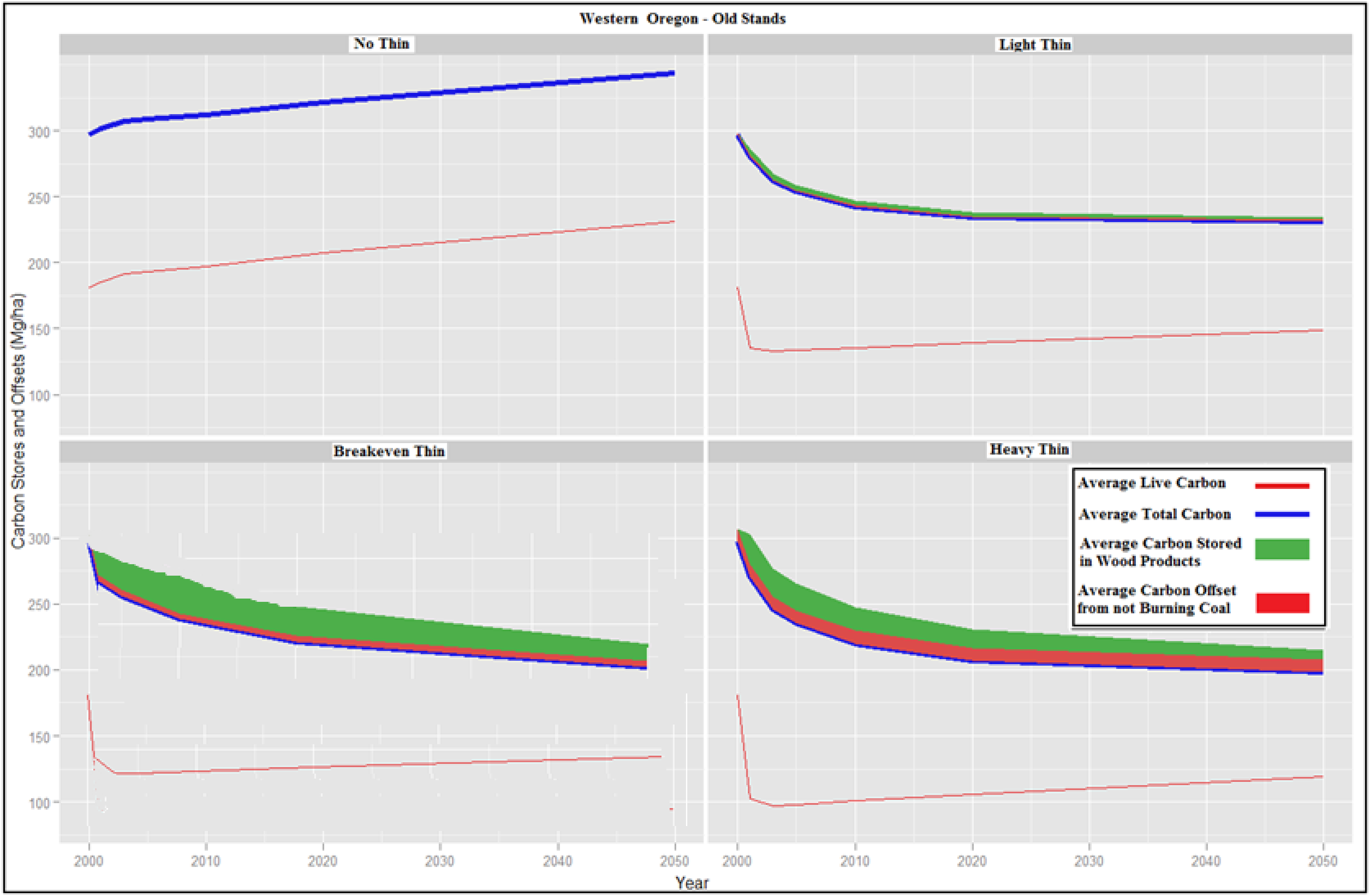


Figure D6. Western Oregon – old stands. Simulation of carbon pools for the forest stand over a 50 year period. Biomass for energy is not included in wood product sequestration – it is assumed utilized within the first year.

Appendix E. Carbon Accounting Methodology Using FVS and other Tools

There are several different methods and tools available to estimate tree-level and/or plot-level carbon. In this analysis, the primary source for biomass and carbon estimates is the FVS-FFE extension. Two components (1-ft stump and bole bark) were estimated manually. All plot carbon stores are included in estimates except for soil carbon. In all components, carbon weight is estimated as 50% of bone-dry biomass weight (see page 325 Penman et al. 2003) except for litter and duff, which is estimated as 37% carbon (Smith and Heath 2002).

Most of the detailed information about FVS calculations was taken from FVS user manuals or from personal communication with developers.

The carbon pools for each plot were estimated as follows:

Aboveground Standing Live (FVS and Allometric Estimates):

Bole Biomass (FVS):

- Bole volume (green) is estimated using equations from the National Volume Estimator Library, based on region, species, diameter at breast height (DBH), height, and other tree-level measurements.
- Specific gravity for the tree species/region is used (Reinhardt et al. 2009) to estimate bole biomass from green volume by the equation Bole Biomass = Green Volume * Specific gravity (Forest Products Laboratory 1999).
- Defects can be accounted for using total volume estimates in FVS, and 15% defect is included for wood products estimates, as in a previous study (Adams and Latta 2003).
- Bole bark is not included in the FVS estimate, but was included manually (see below).
- Stump biomass (from ground to 1 foot height) were not included in FVS-FFE estimates, but they were included manually (see below for stump calculations).

Bole Bark Biomass (Allometric Estimate):

- Estimate from regional biomass estimates (Gholz et al. 1979). Estimates are based on species and DBH.

Stump Biomass (Allometric Estimate):

- The stump not accounted for in the FFE-FVS measurement is 1 ft high. The part of the stump above 0.5 ft is considered part of the bole when harvested, and the part of the stump below 0.5 ft is assumed aboveground biomass left behind if the tree is cut.
- Diameter estimates for stumps are taken from allometric equations (Wensel and Olson 1995). Function of species, DBH, height of DBH measurement.
- The assumed cut height for stumps was 0.5 ft. Stump volume was estimated by dividing the 1-ft stump into 2 frustums, each 0.5 ft high.
- Density is assumed to be a constant (not height dependent) for each species (Bouffier et al. 2003; Megraw 1985). Biomass is calculated as Density*Volume. Carbon is assumed to be 50% of bone-dry weight.

Crown Biomass (FVS):

- Equations based on tree parameters (species, DBH, height, relative dominance in the plot). (Brown and Johnston 1976).
- Crown biomass estimates also based on crown ratio, tree height in stand.
  - If ≥ 60th percentile, then assumed dominant/co-dominant.
  - If < 60th percentile, then assumed suppressed/intermediate.
- The crown is divided into dead/live and material size by diameter (foliage, <0.25”, 0.25”-1”, 1”-3”, >3”).

Aboveground Standing Dead (FVS):

- This component was modeled based on several factors (details in Rebain 2008). Parameters modeled include snag fall (and associated height loss) and decay rates based on several parameters, including regional temperature, moisture class by plant association, years before hard snags become soft snags, soil moisture, soil depth, and soil position.
- All plots have dead trees that are measured and included. Snags are classified as recent mortality or not recent mortality.
- The 0.5 ft stumps left after thinning are also included. A study of decomposition rates of stumps in an old-growth stand of Douglas-fir and western hemlock (Janisch et al. 2005) suggested that log decay rates can be substituted for stump decay rates. In this analysis, the FVS decay rates of course woody debris are applied to stumps. Annual decay rates are 2.5% for stumps less than 3” diameter, and 1.25% for stumps greater than 3” diameter.

Belowground Live (FVS):

- Includes all coarse roots >2mm (0.079 in) in diameter.
- Fine roots are assumed to be part of soil carbon (e.g., Jenkins 2003), and are not estimated.

Belowground Dead (FVS):

- Includes coarse roots >2mm (0.0079 in) in diameter. Smaller roots are not estimated.
- The default root decay rate of 0.0425 is used (Ludovci et al. 2002).

Forest Floor (FVS):

- Includes duff and leaf litter.
- Annual litterfall uses estimates based on Keane et al. 1989, and is a function of species, foliage weight, and leaf lifespan.

Downed Dead Wood (FVS):

- For this pool, the default value is used initially (Reinhardt et al. 2009).

Shrubs and Herbs (FVS):

- Does not dynamically simulate weight of shrubs and herbs, and is assumed roughly constant in a stand, given the understory vegetation associated with a plot.
- Biomass estimates are based on the First Order Fire Effects Model (FOFEM) (Reinhardt et al. 1997).

Conversion from bone-dry biomass weight to carbon

The conversion from bone-dry biomass to carbon is simple. Carbon content for all biomass is assumed to be 50% of bone-dry biomass except for litter and duff which is estimated as 37% of bone-dry biomass.

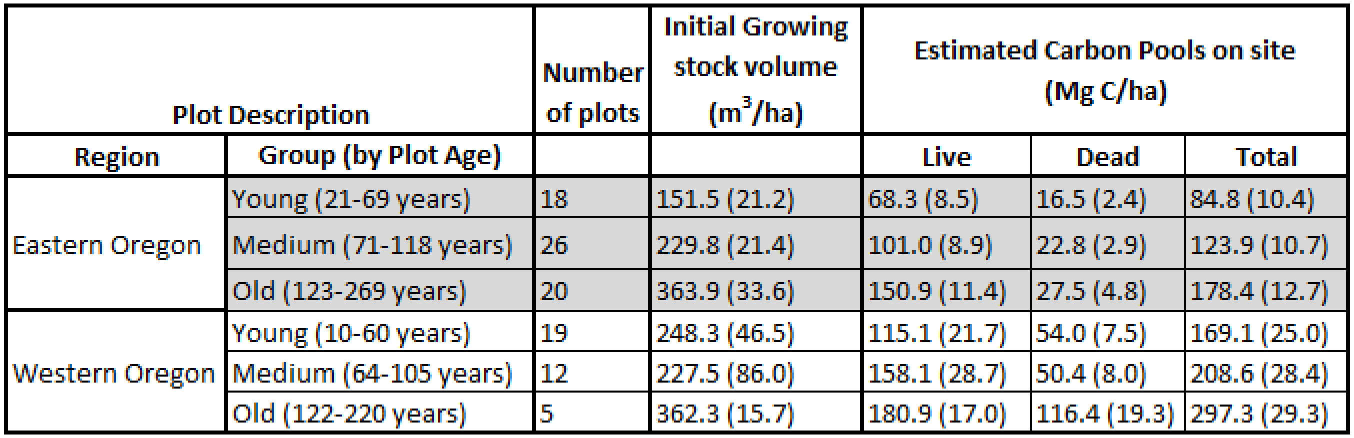
Moisture Content

All moisture content estimates are made using wet basis. This basis estimates water content as a fraction of green weight.

$$MC\ \%_{wet} = \frac{green\ weight - dry\ weight}{green\ weight}\ \text{x 100.}$$

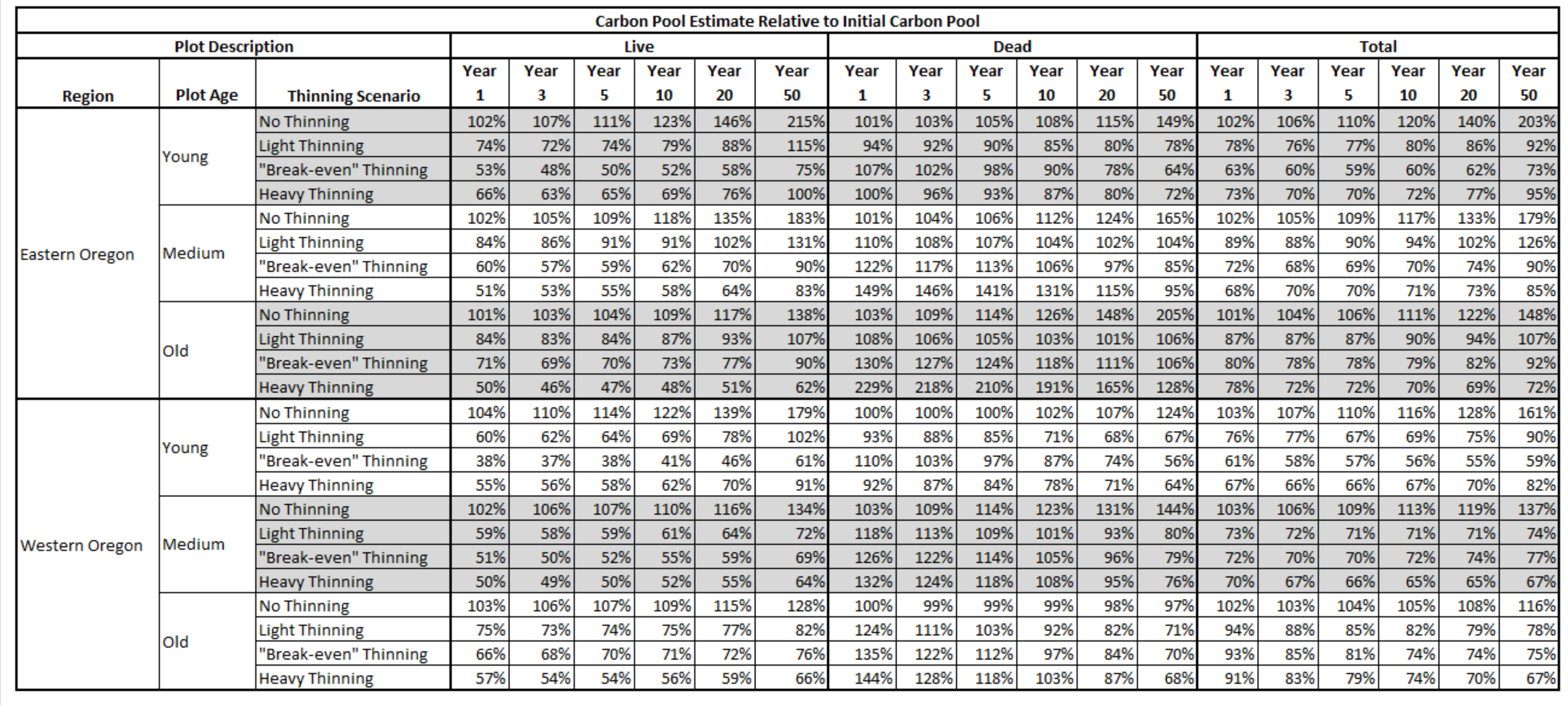
Appendix F. Summary Tables of Carbon Stores, Fluxes, Relative Carbon and Fuel Reduction Measurement.

Table F1. Estimated mean carbon stores with associated standard error for each region/age category. Initial growing stock volume is total volume, not merchantable volume. Carbon pools for each plot are separated into three categories: (1) Live (Aboveground Standing, Belowground Live, Shrubs and Herbs); (2) Dead (Belowground Dead, Standing Dead, Downed Dead Wood); and (3) Forest Floor. Data is presented as: carbon mean [Mg/hectare] (carbon standard error) [Mg/hectare].



Plot Description		Number of plots	Initial Growing stock volume (m^3/ha)	Estimated Carbon Pools on site (Mg C/ha)		
Region	**Group (by Plot Age)**			**Live**	**Dead**	**Total**
Eastern Oregon	Young (21-69 years)	18	151.5 (21.2)	68.3 (8.5)	16.5 (2.4)	84.8 (10.4)
	Medium (71-118 years)	26	229.8 (21.4)	101.0 (8.9)	22.8 (2.9)	123.9 (10.7)
	Old (123-269 years)	20	363.9 (33.6)	150.9 (11.4)	27.5 (4.8)	178.4 (12.7)
Western Oregon	Young (10-60 years)	19	248.3 (46.5)	115.1 (21.7)	54.0 (7.5)	169.1 (25.0)
	Medium (64-105 years)	12	227.5 (86.0)	158.1 (28.7)	50.4 (8.0)	208.6 (28.4)
	Old (122-220 years)	5	362.3 (15.7)	180.9 (17.0)	116.4 (19.3)	297.3 (29.3)

Table F2. Carbon pool estimate relative to initial carbon store where 100% represents the initial mean carbon store of a region/plot age combination before thinning.



Carbon Pool Estimate Relative to Initial Carbon Pool																				
Plot Description			Live						Dead						Total					
Region	Plot Age	Thinning Scenario	Year 1	Year 3	Year 5	Year 10	Year 20	Year 50	Year 1	Year 3	Year 5	Year 10	Year 20	Year 50	Year 1	Year 3	Year 5	Year 10	Year 20	Year 50
Eastern Oregon	Young	No Thinning	102%	107%	111%	123%	146%	215%	101%	103%	105%	108%	115%	149%	102%	106%	110%	120%	140%	203%
		Light Thinning	74%	72%	74%	79%	88%	115%	94%	92%	90%	85%	80%	78%	78%	76%	77%	80%	86%	92%
		"Break-even" Thinning	53%	48%	50%	52%	58%	75%	107%	102%	98%	90%	78%	64%	63%	60%	59%	60%	62%	73%
		Heavy Thinning	66%	63%	65%	69%	76%	100%	100%	96%	93%	87%	80%	72%	73%	70%	70%	72%	77%	95%
	Medium	No Thinning	102%	105%	109%	118%	135%	183%	101%	104%	106%	112%	124%	165%	102%	105%	109%	117%	133%	179%
		Light Thinning	84%	86%	91%	91%	102%	131%	110%	108%	107%	104%	102%	104%	89%	88%	90%	94%	102%	126%
		"Break-even" Thinning	60%	57%	59%	62%	70%	90%	122%	117%	113%	106%	97%	85%	72%	68%	69%	70%	74%	90%
		Heavy Thinning	51%	53%	55%	58%	64%	83%	149%	146%	141%	131%	115%	95%	68%	70%	70%	71%	73%	85%
	Old	No Thinning	101%	103%	104%	109%	117%	138%	103%	109%	114%	126%	148%	205%	101%	104%	106%	111%	122%	148%
		Light Thinning	84%	83%	84%	87%	93%	107%	108%	106%	105%	103%	101%	106%	87%	87%	87%	90%	94%	107%
		"Break-even" Thinning	71%	69%	70%	73%	77%	90%	130%	127%	124%	118%	111%	106%	80%	78%	78%	79%	82%	92%
		Heavy Thinning	50%	46%	47%	48%	51%	62%	229%	218%	210%	191%	165%	128%	78%	72%	72%	70%	69%	72%
Western Oregon	Young	No Thinning	104%	110%	114%	122%	139%	179%	100%	100%	100%	102%	107%	124%	103%	107%	110%	116%	128%	161%
		Light Thinning	60%	62%	64%	69%	78%	102%	93%	88%	85%	71%	68%	67%	76%	77%	67%	69%	75%	90%
		"Break-even" Thinning	38%	37%	38%	41%	46%	61%	110%	103%	97%	87%	74%	56%	61%	58%	57%	56%	55%	59%
		Heavy Thinning	55%	56%	58%	62%	70%	91%	92%	87%	84%	78%	71%	64%	67%	66%	66%	67%	70%	82%
	Medium	No Thinning	102%	106%	107%	110%	116%	134%	103%	109%	114%	123%	131%	144%	103%	106%	109%	113%	119%	137%
		Light Thinning	59%	58%	59%	61%	64%	72%	118%	113%	109%	101%	93%	80%	73%	72%	71%	71%	71%	74%
		"Break-even" Thinning	51%	50%	52%	55%	59%	69%	126%	122%	114%	105%	96%	79%	72%	70%	70%	72%	74%	77%
		Heavy Thinning	50%	49%	50%	52%	55%	64%	132%	124%	118%	108%	95%	76%	70%	67%	66%	65%	65%	67%
	Old	No Thinning	103%	106%	107%	109%	115%	128%	100%	99%	99%	99%	98%	97%	102%	103%	104%	105%	108%	116%
		Light Thinning	75%	73%	74%	75%	77%	82%	124%	111%	103%	92%	82%	71%	94%	88%	85%	82%	79%	78%
		"Break-even" Thinning	66%	68%	70%	71%	72%	76%	135%	122%	112%	97%	84%	70%	93%	85%	81%	74%	74%	75%
		Heavy Thinning	57%	54%	54%	56%	59%	66%	144%	128%	118%	103%	87%	68%	91%	83%	79%	74%	70%	67%

Table F3. Torching Index and Crowning Index estimates.

Torching Index is the wind speed at which crown fire is expected to initiate (based on Rothermel (1972) surface fire model and Van Wagner (1977) crown fire initiation criteria. Crowning Index is the wind speed at which active crowning fires are possible (based on Rothermel (1991) crown fire spread rate model and Van Wagner (1977) criterion for active crown fire spread). Wind speed refers to speed of wind measured 20 ft above the canopy. Lower values indicate higher susceptibility. Data is presented as: crowning/torching index [mi/hr] (standard deviation) [mi/hr] for select years. Red indicates that plots would benefit from a thinning using the criteria in this study. Orange indicates the average was still below criteria following the thinning, and green indicates that the average index for plots was above the minimum criteria used in this study.

Plot Description			Crowning Index (mi/hr)							Torching Index (mi/hr)						
Region	Plot Age	Thinning Scenario	Year 0 After Thinning	Year 1	Year 3	Year 5	Year 10	Year 20	Year 50	Year 0 After Thinning	Year 1	Year 3	Year 5	Year 10	Year 20	Year 50
Eastern Oregon	Young	No Thinning	**39.3 (24.7)**	**39.3 (24.7)**	**38.7 (23.8)**	**37 (20.9)**	**30.5 (16.5)**	**28.7 (15.3)**	**25.1 (12.0)**	52.2 (55.6)	48.3 (47.2)	49 (46.4)	51.3 (44.1)	54 (37.9)	84.4 (82.2)	117 (96.4)
		Light Thinning	78 (45.6)	78 (45.6)	89.1 (54.9)	88.6 (55.0)	75.3 (46.6)	72 (44.7)	65.7 (45.7)	38.6 (23.2)	38.5 (23.1)	43.8 (24.0)	45.6 (25.2)	44 (22.4)	50.7 (26.6)	67.4 (44.8)
		"Break-even" Thinning	89 (23.0)	89 (23.0)	102 (32.1)	103.4 (35.4)	87.6 (30.3)	83.6 (30.7)	76.4 (33.0)	29.4 (14.0)	29.4 (14.0)	33.5 (13.6)	35.9 (13.1)	37.2 (20.1)	39.6 (22.4)	47.1 (15.5)
		Heavy Thinning	66.4 (18.1)	66.4 (18.1)	77.7 (25.0)	78.2 (25.0)	65.9 (21.0)	63.2 (21.1)	57.5 (22.8)	35.4 (16.9)	35.4 (16.8)	45.1 (23.3)	48 (25.3)	44.4 (25.0)	44.6 (19.1)	55.1 (22.0)
	Medium	No Thinning	**35.1 (13.1)**	**35.1 (13.1)**	**35.1 (13.5)**	**34.4 (13.1)**	**29.7 (11.1)**	**27.3 (9.8)**	**24.3 (9.8)**	155.9 (184.4)	143.3 (180.7)	143.8 (183.7)	137.3 (145.9)	122.6 (133.3)	120.6 (127.2)	118 (108.6)
		Light Thinning	45.7 (19.6)	45.7 (19.6)	50.7 (23.3)	49.9 (22.9)	43.6 (20.5)	41.1 (19.5)	**37.6 (19.6)**	113.3 (197.3)	107.5 (176.2)	114.5 (174.4)	118.1 (179.9)	100.2 (126.0)	115.6 (125.8)	140.4 (145.3)
		"Break-even" Thinning	65.9 (26.4)	65.9 (26.4)	72.1 (30.2)	71.7 (30.4)	63.1 (27.1)	60.6 (28.0)	55 (28.4)	40.6 (19.8)	41 (20.4)	45.9 (22.2)	49 (22.5)	49.9 (25.5)	60.2 (36.8)	77.2 (64.9)
		Heavy Thinning	71.6 (34.5)	71.6 (34.5)	74.9 (34.7)	73.6 (33.2)	64.3 (30.8)	60 (27.9)	53.8 (24.9)	43.9 (26.9)	44.3 (27.6)	50.1 (31.2)	54.7 (34.1)	54.3 (33.6)	66.3 (54.7)	85.2 (73.4)
	Old	No Thinning	**39.9 (17.3)**	**39.9 (17.3)**	**40 (17.0)**	**39.5 (16.7)**	**37.4 (17.1)**	**34.9 (15.5)**	**33.7 (15.4)**	155.4 (163.7)	154.4 (165.1)	162.8 (173.0)	171.1 (181.3)	158.3 (156.8)	146 (155.7)	98.1 (95.7)
		Light Thinning	59.1 (25.9)	59.1 (25.9)	69.2 (31.1)	69.2 (31.8)	66.8 (34.0)	66 (35.8)	63.4 (37.0)	98.8 (110.9)	101.8 (114.5)	106.4 (115.5)	109.7 (121.4)	116.9 (139.3)	132.8 (155.9)	76.5 (66.2)
		"Break-even" Thinning	68.1 (26.1)	68.1 (26.1)	79.4 (32.3)	79.1 (32.6)	76.1 (35.1)	74.7 (36.7)	71.1 (38.2)	81.5 (87.8)	80.7 (88.0)	95.3 (93.9)	98.7 (99.1)	105.7 (113.7)	122.2 (132.8)	149.3 (158.8)
		Heavy Thinning	128.8 (93.1)	128.8 (93.1)	130.4 (89.5)	127.2 (87.2)	115.8 (82.3)	104.2 (72.6)	100.8 (79.4)	48.7 (29.7)	49 (29.6)	56.3 (35.6)	59 (35.0)	61.8 (31.1)	68.7 (31.0)	89.5 (42.2)
Western Oregon	Young	No Thinning	**36.1 (40.3)**	**36.1 (40.3)**	**37 (43.6)**	**37.1 (44.6)**	**27.3 (29.9)**	**24.1 (20.6)**	**21.6 (14.2)**	92.2 (98.4)	87.5 (106.3)	84 (128.6)	69 (75.8)	58.9 (72.9)	90.2 (148.8)	141.5 (218.3)
		Light Thinning	56.5 (58.8)	56.5 (58.8)	56.3 (58.6)	56.2 (58.3)	46.3 (48.9)	45.9 (48.3)	45.4 (47.0)	98.7 (81.6)	96.5 (80.6)	95 (79.2)	92 (75.7)	66.8 (52.9)	73.9 (53.9)	92.3 (58.4)
		"Break-even" Thinning	82.6 (96.2)	82.6 (96.2)	82.2 (95.6)	81.8 (95.1)	66.5 (76.9)	65.2 (75.3)	63.7 (72.5)	75.6 (70.0)	75.4 (68.6)	74.7 (66.2)	76.1 (65.0)	54.1 (44.4)	60.3 (41.3)	78.2 (43.3)
		Heavy Thinning	59.3 (57.0)	59.3 (57.0)	58.9 (56.9)	58.9 (56.6)	48.5 (47.4)	48.1 (46.8)	47.8 (45.5)	88.7 (78.8)	87.2 (77.1)	87.2 (74.7)	85.9 (69.7)	62.7 (47.3)	69.9 (48.2)	90.5 (53.2)
	Medium	No Thinning	**20.3 (19.0)**	**20.3 (19.0)**	**20.2 (18.3)**	**20.2 (17.8)**	**15.3 (14.2)**	**15.1 (13.5)**	**15.5 (12.6)**	56.7 (175.0)	61.8 (199.9)	73.6 (247.5)	72.6 (247.7)	67.5 (248.7)	69.3 (248.3)	85.2 (253.6)
		Light Thinning	26.4 (32.4)	26.4 (32.4)	27.5 (33.3)	27.4 (33.0)	**21.3 (26.6)**	**20.9 (25.5)**	**20.8 (23.7)**	64.1 (163.1)	64.1 (163.1)	71 (184.3)	84.1 (231.2)	76.7 (239.9)	79.7 (240.1)	93 (237.0)
		"Break-even" Thinning	38.7 (60.0)	38.7 (60.0)	40.3 (60.3)	40.6 (59.9)	31.8 (47.5)	31.2 (45.3)	30.8 (41.7)	61.8 (168.5)	62.3 (168.1)	65.1 (167.9)	65.8 (169.6)	41.4 (109.6)	46.1 (114.4)	60.3 (120.9)
		Heavy Thinning	30.7 (33.0)	30.7 (33.0)	32 (34.1)	32.1 (33.7)	25.4 (27.0)	25.8 (25.7)	27.2 (23.0)	59.5 (161.5)	59.5 (161.6)	68.6 (183.1)	80.1 (229.8)	75.2 (239.5)	78.7 (239.8)	88 (237.6)
	Old	No Thinning	**14.7 (4.8)**	**14.7 (4.8)**	**15.8 (5.9)**	**15.5 (5.1)**	**12.5 (5.3)**	**13.7 (6.4)**	**15.2 (5.5)**	**7.9 (14.0)**	**8.4 (14.8)**	**12.3 (22.4)**	**14.9 (24.7)**	**9.2 (16.9)**	**14.4 (21.2)**	36 (25.8)
		Light Thinning	**26.9 (20.0)**	**26.9 (20.0)**	**28.8 (21.8)**	**28.3 (21.9)**	**22.5 (17.6)**	**23.1 (17.1)**	**23.3 (15.7)**	31 (41.1)	33.5 (43.5)	51.4 (70.4)	55.8 (71.0)	35.7 (46.1)	45 (49.4)	63.1 (55.4)
		"Break-even" Thinning	42.6 (31.1)	42.6 (31.1)	46.9 (36.3)	46.4 (36.2)	36.7 (28.8)	37 (26.8)	36.1 (23.7)	25.3 (39.0)	26.4 (41.2)	30 (46.0)	31.6 (48.8)	**18.4 (30.3)**	26.3 (35.3)	49.1 (41.5)
		Heavy Thinning	33 (18.7)	33 (18.7)	35.1 (20.6)	34.7 (20.3)	27.8 (16.2)	29 (15.8)	28.8 (13.2)	27.3 (43.0)	29 (45.8)	44.3 (73.9)	46.3 (75.6)	28.8 (48.9)	38.6 (51.0)	61.7 (56.4)

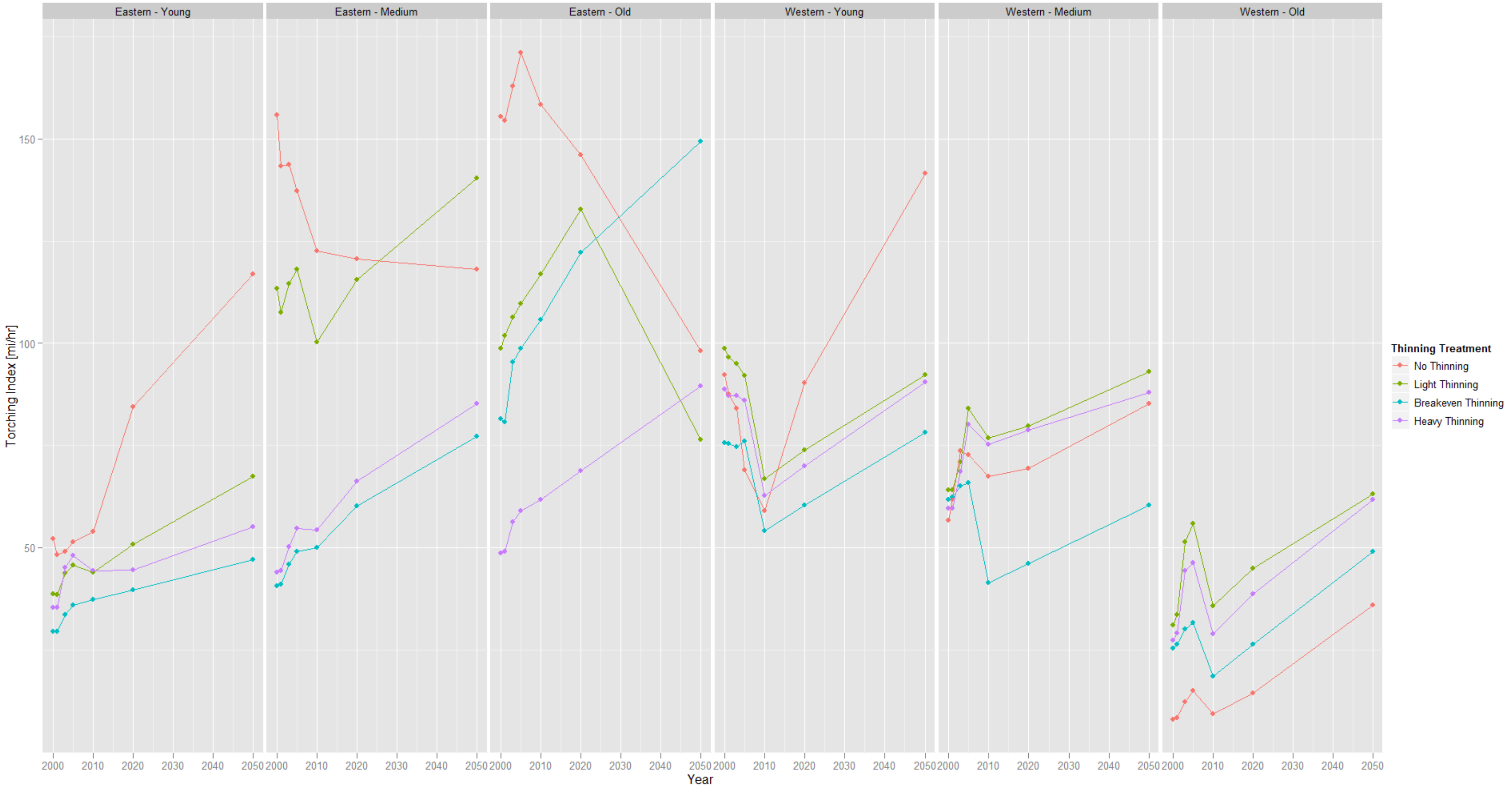


Figure F1. Torching Index (mi/hr) over a 50 year period – comparison is for different treatments for region/age combinations. This is a graphical representation of the means (averages) from Table F3, and does not include variance, which is relatively high compared to the mean.

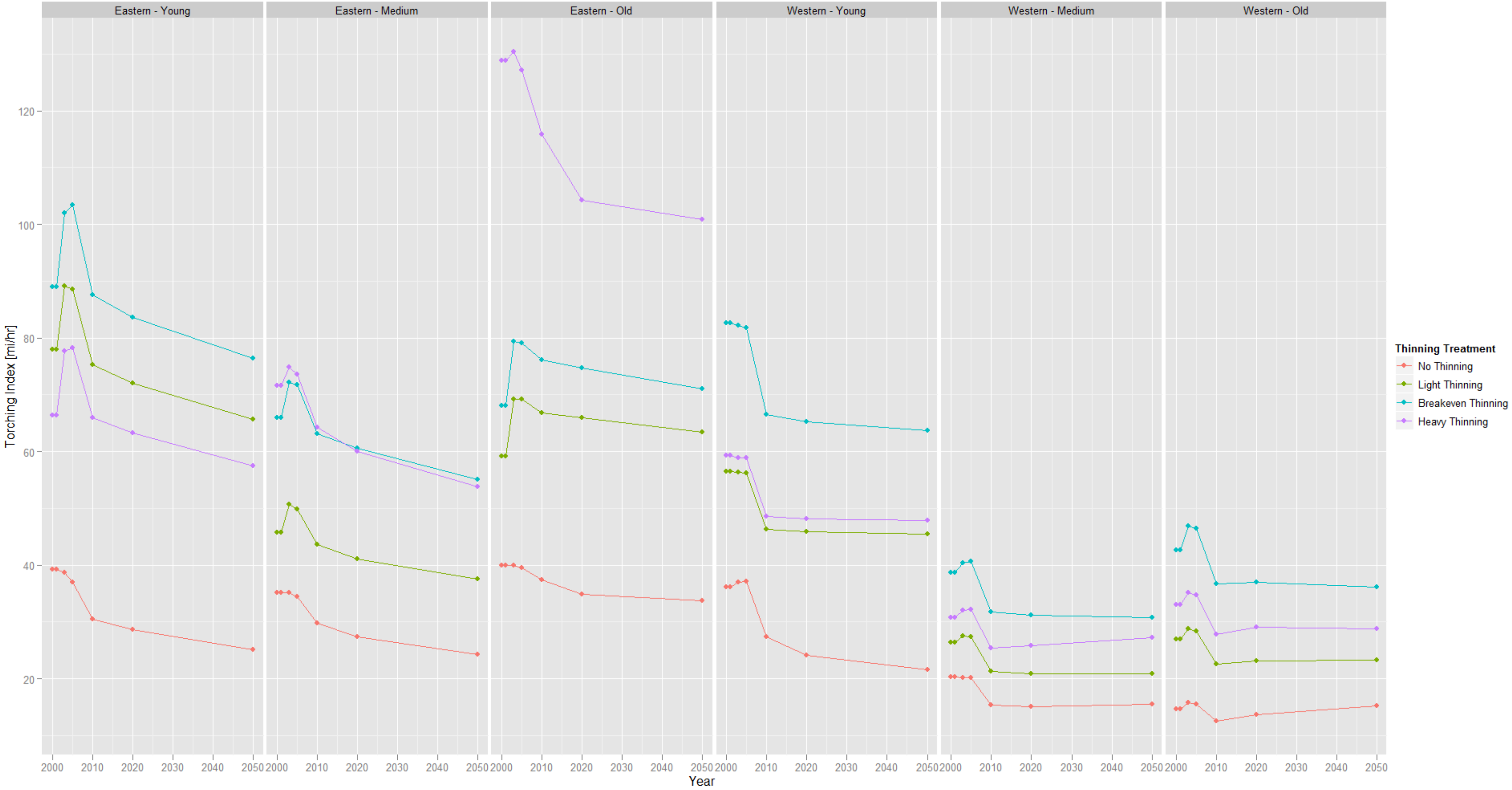


Figure F2. Crowning Index (mi/hr) over a 50 year period – comparison is for different treatments for region/age combinations. This is a graphical representation of the means (averages) from Table F3, and does not include variance, which is high relative to the mean.

Table F4. Number of plots within each region and age group with the greatest amount of Live, Dead, and Total Carbon stores for each thinning scenario vs. no thinning scenario. As seen in this table, carbon stores in a plot following a thinning are always lower for every plot used in this analysis.

Number of plots for each scenario with the largest carbon store																				
Plot Description			Live						Dead						Total					
Region	Plot Age	Thinning Scenario	Year 1	Year 3	Year 5	Year 10	Year 20	Year 50	Year 1	Year 3	Year 5	Year 10	Year 20	Year 50	Year 1	Year 3	Year 5	Year 10	Year 20	Year 50
Eastern Oregon	Young	No Thinning	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
		Light Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		"Break-even" Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Heavy Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Medium	No Thinning	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26
		Light Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		"Break-even" Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Heavy Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Old	No Thinning	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
		Light Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		"Break-even" Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Heavy Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Western Oregon	Young	No Thinning	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
		Light Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		"Break-even" Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Heavy Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Medium	No Thinning	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
		Light Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		"Break-even" Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Heavy Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Old	No Thinning	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
		Light Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		"Break-even" Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Heavy Thinning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix G. Conversion Units and Definitions.

Conversion factors from metric to imperial units.

1 hectare (ha) = 2.471 acre (ac)
1 meter (m) = 3.281 feet (ft)
1 square meter (m^2) = 10.764 square feet (ft^2)
1 cubic meter (m^3) = 35.315 cubic feet (ft^3)

1 megagram (Mg) = 1000 kilograms (kg) = 1 metric tonne = 1.102 short tons
1 short ton = 2000 pounds (lbs)

1 kilowatt-hr (kWh) = 3413 British Thermal Units (BTU)

Definitions from IPCC FAR used in this report (IPCC 2007):

- Reservoir – "a component of the climate system other than the atmosphere which has the capacity to store, accumulate or release… greenhouse gas..."
- Sink – "any process, activity or mechanism that removes a greenhouse gas … from the atmosphere."
- Source – "any process, activity or mechanism that releases a greenhouse gas… into the atmosphere."