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Final Report
LandCarb Simulation of Forest Carbon Flux in Oregon

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Introduction. The purpose of this report is to provide a final report related to supplying information needed for the Oregon Indicator of Sustainable Forest Management G.a.., "Carbon stocks on forestlands and in wood products." The methods and results of a preliminary analysis based on remotely sensed forest age and disturbance data layers and the LandCarb simulation are presented. In addition to this report, the spatial databases compatible with ArcMap have been provided for the stores and fluxes (i.e., net changes in time) of major carbon pools including, live, dead, soil, and forest products, as well as totals of all these pools. We anticipate that additional work will be required to check all the generated databases against inventory and other field data to improve model parameterizations as well as to improve the pre-1970 land-use and disturbance history that required to "spin-up" the simulations. This work will continue under a NASA funded effort over the upcoming year. Nonetheless, the work described here produced the final products outlined in the agreement between OSU and ODF.

Background. Management of carbon storage in forest ecosystems has become a major concern of resource agencies at all levels of government. Many agencies are being asked to inventory and account for their forest carbon stores and biogenic emissions as well as to project the expected changes given current and alternative future management systems. Unfortunately few of these agencies have the expertise or analytical tools in place to routinely perform this crucial task. This is the case for the Oregon. The state has adopted the Montreal Process Criteria and Indicators structure to assess forest sustainability through ecological, economic, and social dimensions. As part of that structure, the Carbon Indicator was designed to track the status of carbon stocks in various pools and their changes within the forested ecosystems of Oregon. The Oregon Department of Forestry is tasked with reporting on several indicators including carbon.

In this project we have integrated remote sensing and computer simulations to monitor trends in actual carbon dynamics in Oregon's forests. This will help meet Oregon's commitment to carbon accounting and reporting through the Montreal Process. This work will eventually be used to detect and quantify changes in forest carbon stocks (including fine-scale changes) on all forestland, assist in tracking changes in carbon offset projects, and allow Oregon to examine the potential for alternative management systems to increase carbon sequestration. This report describes the first phase of using this system.

Products Provided. The following products are provided in this report and associated databases:

1. A set of raster databases for each of four regions within Oregon in the form of Arc ADF files. Each raster database represents a 50 km by 50 km area (30 mile by 30 mile). Each raster is 100 m by 100 m, (328 feet by 328 feet), but the data are presented metric tons per hectare of carbon matter for stores and metric tons of carbon per hectare per year for the fluxes.

2. Each set of rasters consist of layers representing the historic maps of carbon stores, sources, and sinks from 1960 to 2010 at yearly intervals. The specific pools output were total live carbon (trees, shrubs, herbs, and grasses), total dead carbon (foliage, wood, roots, above- and belowground), total soil or stable pools (duff and mineral soil), forest products in use, harvested carbon, and total of all the forest pools (this version does not include forest products). Although the forest products stores are depicted on these databases, it really represents the stores associated with the harvest from a given site and not the store of forest products on the site. Both the stores at a given year and the average change in these stores (i.e., the flux) is presented.

3. This report describes the state of software, methods and assumptions used, and the state project development.

4. A analysis of general conclusions for each of the four regions regarding current conditions and recent trends for carbon storage and sequestration and on the quality and limitations of the available information to form those conclusions.

5. Recommendations for next steps to develop comprehensive, repeatable statewide condition and trend monitoring of carbon stocks in Oregon forestlands and forest products.

Study Areas. Since we were using this system for the first time we concentrated our efforts on four study areas that reflect the diversity of forest systems in Oregon (Figure 1). This included Landsat scenes in: 1) the Klamath region of southwestern Oregon where mixed conifer forests dominate and there has been a recent increase in wildfires; 2) the Central Western Cascades region, which holds significant carbon-sequestration potential, and which is a major timber producing area dominated by Douglas-fir/western hemlock; 3) the high Cascades and Eastern Cascades, which are dominated by true firs, Douglas-fir, and ponderosa pine, and which have seen significant insect and fire-related mortality in the Landsat era, and 4) the Blue Mountains of eastern Oregon, which include a range of forest types typical of the interior west, with a similar mix of fire and insect activity and a diversity of harvest intensities and goals.

Remote Sensing Databases. Although Landsat data are not direct measures of carbon, Landsat-derived landcover and disturbance products provided constraints on both starting carbon condition and on the spatial and temporal patterns of change in carbon initiated by disturbance. Three products derived from Landsat data were central to this effort. The first a GNN-derived age maps for the 2001 era. The GNN (Gradient Nearest Neighbor) approach integrates Landsat data with a variety of environmental variables to impute FIA-plot data across an entire landscape (Ohmann and Gregory 2002). This database allowed us to create a disturbance history prior to 1972 that was used to allow the LandCarb model to “spin-up” to the period of interest. The second product was a 5-year periodic disturbance database for the 1972-1982 period based on a change detection comparison of Landsat images over roughly 5 year intervals. In the Blue Mountains region this product was used for the entire1972-2008 period. To create an annual disturbance database from the 5 –year intervals, we divided each region into XX subregions and for each year selected a proportion to have disturbance in that year. The proportion was a function of the interval length (e.g., if the interval was 5 years, then 20% were selected each year). If a selected subregion did not happen to have a disturbance in the 5-year interval, then disturbance did not occur in the subregion even if it was selected. The third product, an annual disturbance database for the 1982-2008 period, was derived for the western and eastern Cascades as well as the Klamath region using LandTrendr – Landsat Detection of Trends in Disturbance and Recovery (Kennedy et al. 2007). In this case disturbances occurred in the year they were detected. All spatial databases were rescaled from the original 30 m by 30 m raster cells to 100 m by 100 m.

The Simulation Model. Simulation modeling used the LANDCARB 3.0 model which simulates the accumulation of carbon over time in a landscape with mixed species/mixed aged forest stands and spatially variable climate, soil, topography, and history. The model can be used to investigate the landscape level effects of various regeneration strategies, harvesting, herbicide application, salvage, patch cutting, tree species replacement by design or by natural succession, site preparation, and wildfires. However, in this analysis we focused on stand-replacing disturbances and assumed that these all resulted from either a stand-replacing wildfire or a clearcut harvest.

LANDCARB 3.0 has a number of levels of organization it uses to estimate changes in carbon stores within a landscape. At the highest level there is a landscape comprised of stand grid cells, which in these simulations were 100 m by 100 m. Each stand grid cell potentially contained a number of cohorts that represent different episodes of disturbance and colonization, although because we only addressed stand-replacing disturbances it is likely that only one cohort existed per stand grid cell. Each cohort contained four layers of vegetation each having up to seven live parts, eight dead pools, three stable pools representing highly decomposed material, and two pools representing charcoal. The four layers of vegetation that occurred in each cohort were upper trees, lower trees, shrubs, and herbs. Each layer of plants had an age-class structure reflecting gradual colonization of each cohort. Each cohort has seven live parts: 1) foliage, 2) fine roots, 3) branches, 4) sapwood, 5) heartwood, 6) coarse roots, and 7) heart-rot. Each of the live parts of each layer contributed material to a corresponding dead pool. Thus foliage added material to the dead foliage, etc. All the dead pools added material to one of three stable pools (stable foliage, stable wood, and stable soil). Finally, fires created surface charcoal from live parts or dead pools. Surface charcoal were incorporated into the mineral soil and became protected from future fires as buried charcoal, whereas surface charcoal was lost during subsequent fires. In addition to these forest ecosystem pools, we programmed the model to track the stores of forest products resulting from timber harvest. We assumed that 50% of the harvested carbon was lost during processing and initial use, and that 1% was lost per year when forest products were in use.

Simulation Runs. Each region was divided into 3 climatic/seed/productivity zones based on elevation. Forest productivity was assumed to be highest in the western Cascade region (Appendix 1), 30% lower in the east-side Cascade, 35% lower in the Klamath, and 50% lower in the Blue Mountain regions. This was based on a state-wide spatial database created by Swenson et al (2005). Within regions we altered the level of forest productivity by elevation, with the lowest elevation zone having 10% less productivity than the middle elevation zone assuming there was a moisture limitation. The highest elevation zone had 15% less productivity than the middle elevation zone assuming there was a temperature/growing season limitation. We used different species mixtures among forest regions and elevation zones (Appendix 2).

In these simulation runs we used a simplified the forest history prior to 1960 and had “spin-up” prior to the period of analysis of 500 years. Therefore, if a forest was disturbed in 1960, we assumed that it was 500 years of age (the period of the spin-up) when it was disturbed. If the forest was disturbed before 1960, as indicated by the age-class data layer, then we assumed an age less than 500 years when it was disturbed. If the forest was disturbed after 1960 it was assumed to be 500 plus years of age when disturbed. If for example the forest was 100 years of age in 1960, then we assumed the forest was disturbed in year 400 of the spin-up. We assumed that all stand-replacing disturbances prior to 1900 were associated with wildfire and after that point with clear-cut harvesting.

Results of Preliminary Analysis of the Four Regions. An example of a stores grid for 2005 for the west Cascades region is illustrated in Figure 2. Areas in white are lands without forest (i.e., agricultural lands or water). Maximum carbon stores in this area are estimated to be 834 MgC/ha, whereas the minimum was estimated to be 212 MgC/ha. The average for the image is approximately 481 MgC/ha, which is within the range one might expect for this relatively productive forest region, with major old-growth remnants remaining.

An example of flux grid is shown in Figure 3 for the western Cascades for the 2004-2005 period. The majority of the area appears to be a carbon sink, but a few areas have a very high carbon source value to the atmosphere (<100 MgC/ha/year) associated with recent timber harvest. The average landscape flux for the forest ecosystem was estimated to be -0.808 MgC/ha/year. When the fluxes associated with wood products are also considered the average flux for this landscape was estimated to be -0.381 MgC/ha/year. The lower source was due to the fact that some of the losses from the ecosystem were being stored in wood products. Examining the distribution of sources and sinks, it is clear that cuts from several decades ago are the locations with the highest carbon sink potential, which was as high as 8 Mg C/ha/year (a positive flux).

Changes in each of the areas from 1961 to 2008 are indicated in Table 1. With the exception of the Blue Mountains there appears to have been a general decline in carbon stores in the forest sector over this period in all regions. Regardless of the time period, average carbon stores are highest in the west Cascades, a result of the generally higher level of productivity. West Cascades appears to be the only region that is still a carbon source by the 2004 to 2008 period, although this is likely to change in the next decade if reduced harvesting continues in that region.

Table 1. Average stores and fluxes of all forest associated carbon for the four test regions examined at the start and end of the monitoring period.

Region	Total Store 1961	Total Store 2008	Flux 1962-67	Flux 2004-08
	Mg C/ha	Mg C/ha	Mg C/ha/year	Mg C/ha/year
Klamath	315	308	-0.09	0.03
West Cascades	567	529	-0.14	-0.42
East Cascades	357	347	-0.11	0.23
Blue Mountains	310	310	0.15	0.28

The Klamath region appears to currently be in a carbon balance, whereas the East Cascades and Blue Mountains are likely weak carbon sinks.

The trend over time for the western Cascades is illustrated in Figures 4 and 5. The simulations indicate that there has been a decline in average total carbon stores until 2005. These changes have largely been driven by a decline in the live carbon stores and occurred even when stores in wood products were considered. The carbon stores in dead material, wood products, and stable forms (e.g., mineral soil) increased over this period, but not sufficiently to offset the losses in live carbon. Until recently the ecosystem and total forest sector (including wood products) fluxes was generally negative corresponding to the decrease in carbon stores. The negative fluxes greatly increased in the 1970's reaching the highest values in the 1980 to 1990 period. From 1990 to the current period, the size of the negative flux has gradually declined and this forest may be coming into a balance. Without any further disturbances, this area is likely to become a carbon sink during the 2008-2010 period. However, that is extremely unlikely to happen.

One behavior that bears additional analysis is the speed at which the landscape carbon flux can switch from positive to negative and vice versa. We believe this is caused by the fact that very small areas of sources are required to offset very large areas of sinks. This is because on per area basis, sources are much larger than sinks. Therefore a slight change in the area in sources has a very large impact on the average landscape carbon flux.

Extrapolation to the State Level

We extrapolated to the state-wide level by averaging the results from the four regions and multiplying by the total area of productive forest land in Oregon (9.56 million ha) reported by Bolsinger and Wadell (1993). We weighted the results of the four regions by the area they represented of Oregon's forests. A major region not examined in our analysis was the Coast Range, which was assumed to be similar to the west Cascades region. However, the proportion of private lands is likely higher in the Coast Range and the productivity is higher.

Our analysis indicates that Oregon's forest sector currently stores approximately 3,744 Tg (10^{12}). The trend since 1960 has generally been downward (Figure 6), although there may have been some stabilization in most recent years of both the ecosystem and total forest sector-related carbon stores. Carbon fluxes for the forest ecosystems and the combined forest sector appears to have been negative most of the 1970 to 2005 period, indicating that the Oregon forest sector has been a net source of carbon to the atmosphere. Since that time fluxes have been neutral to slightly positive, indicating the system may be switching to a sink from the atmosphere. Over the 1961-2008 period, the average flux was -3.55 Tg C/year. That amount is about 20% of the value of Oregon's greenhouse gas emissions which totaled 18 Tg C/year in 2000. If the fluxes observed in the 2004 to 2008 period continue, then Oregon's forests are now offsetting about 0.14 Tg C/year or less than 1% of the State's greenhouse gas emissions expressed as carbon equivalents.

Recommendations for Improvements. There are several areas for improvements based on our experience.

1. Climatic variability within the regions is an important factor controlling carbon stores and fluxes. We used 3 climatic zones divided along an elevation gradient to represent differences in temperature and precipitation. While this stratified the regions, it created obvious zonation that was not realistic. In future simulations variation in soil properties (i.e., water holding capacity) and solar radiation (dependent largely on slope and aspect) should also be considered. This would greatly increase the number of climate zones and the results would appear more continuous.
2. The effects of climate were largely restricted to respiration losses in this set of simulations. We reduced productivity of the lower elevation zone to account for water limitations. We also reduced productivity of the higher elevation zone to account for temperature limitations. In the future the direct climate effects on photosynthesis via temperature and water availability should be included.
3. Variation in the abundances of tree species within the regions was included by subdividing by elevation zones in to seed zones. A more realistic depiction of seed zones could be developed using potential vegetation maps instead of only elevation zones.
4. The impact of historical legacies on carbon stores is extremely important. Using a 500 versus 300 year period for the model to spin-up and to recreate the forest disturbance history improved the realism of the simulations. The next step will be to create a more realistic spin-up based on spatial databases of past disturbance history.
5. Historical variation in the manufacturing efficiency and longevity of wood products should be considered. In these simulations, we used an average manufacturing efficiency of 50%, but that has likely varied from 40 to over 60% in the last century. In addition, wood products are likely longer lived after the 1970's than before, largely due to the advent of landfills for waste and product disposal. Prior to this time, much of the waste was incinerated or consumed in fires associated with open dumps.
6. Other forest regions within Oregon, such as the northern Coastal Range should be run. Eventually all forest lands within Oregon should be considered. Perhaps the most limiting issue at this point is a spatial database reconstructing the history of disturbance within Oregon. Based on the current processing time, it would likely take 4 weeks to produce a wall-to-wall state-level analysis assuming all the disturbance, climate, soil, and forest history datasets were ready.

Future Plans. Work on the project will continue as part of a NASA sponsored grant, which in addition to the improvements noted above, will also involve comparisons of simulation predictions to FIA databases. This project will also develop a system to project future changes in wildfire and timber harvest that will allow one to project future changes in carbon stores and fluxes associated with Oregon's forests.

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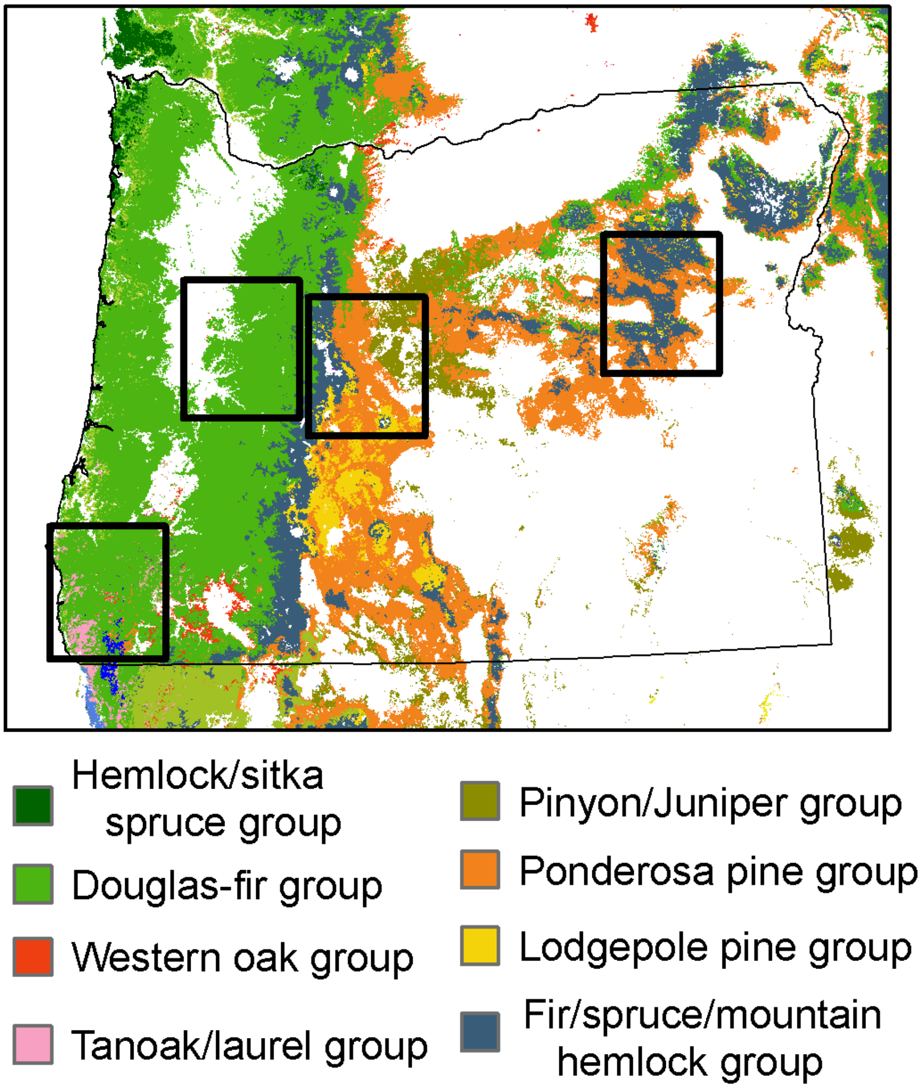

Figure 1. Proposed study areas capturing forest types in Oregon. 1. Klamath region 2. West cascades 3. Cascade crest and east cascades 4. Blue mountains

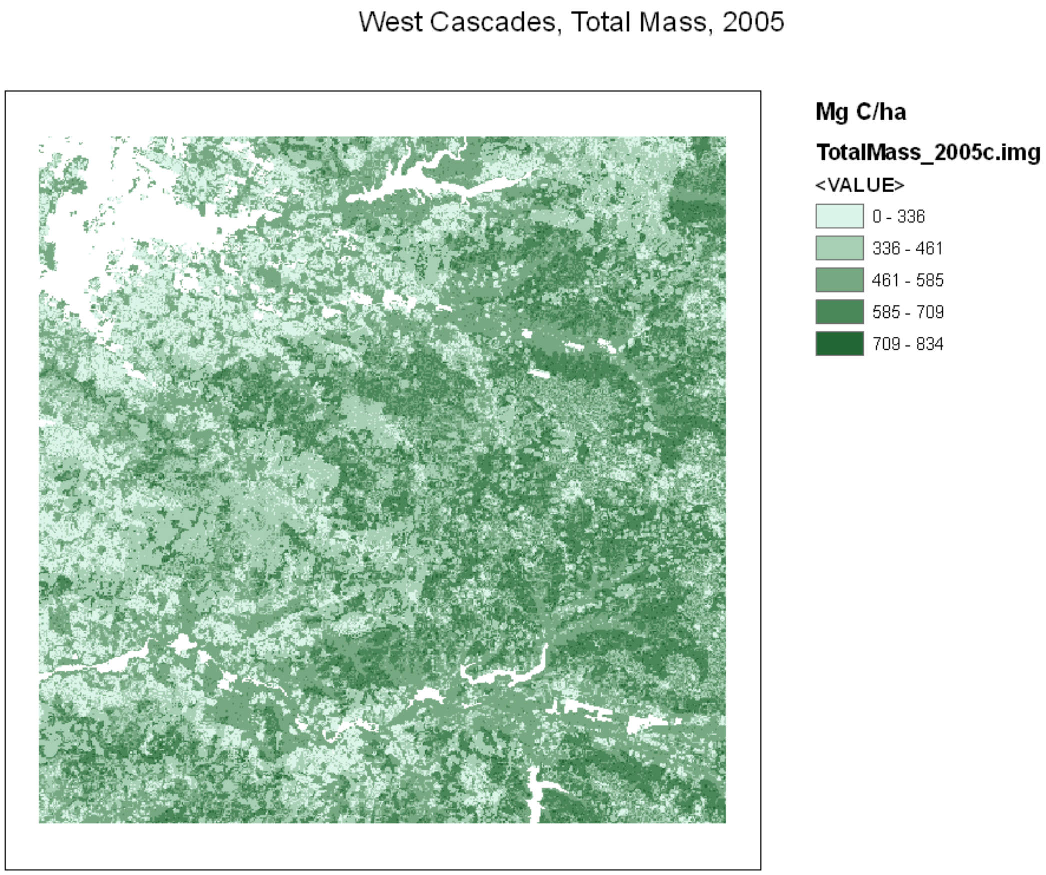

Figure 2. Example of total carbon stores for the western Cascades scene in 2005. Areas in white were classified as non-forest. Maximum carbon stores in this area were estimated to be 834 MgC/ha, whereas the minimum was estimated to be 212 MgC/ha. The average for the image was approximately 481 MgC/ha

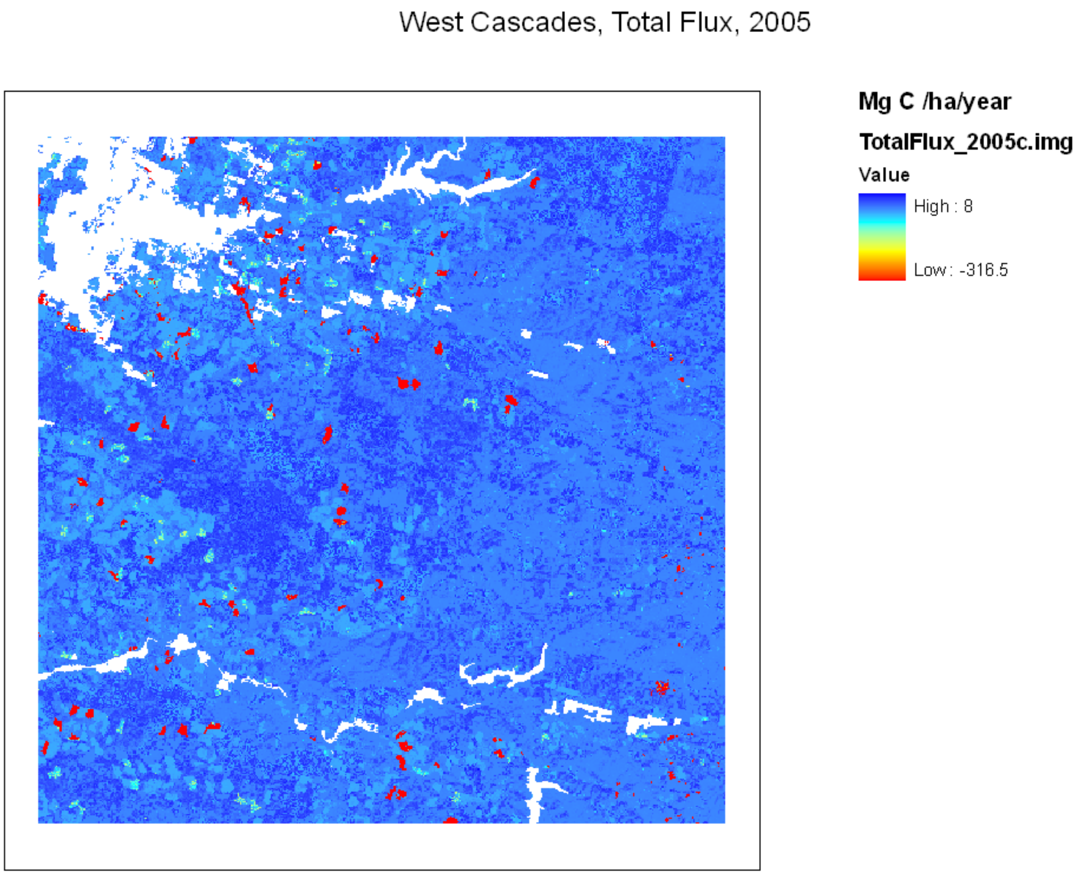

Figure 3. Total carbon flux (MgC/ha/year) in western Cascade test area for 2005. Areas in white were classified as non-forest. Yellow to red areas indicate sources to the atmosphere. Blue areas represent sinks relative to the atmosphere. Note that this landscape was estimated to be a carbon source to the atmosphere of -0.8 MgC/ha/year. This implies that a very small area in sources can offset an extremely large area of sinks.

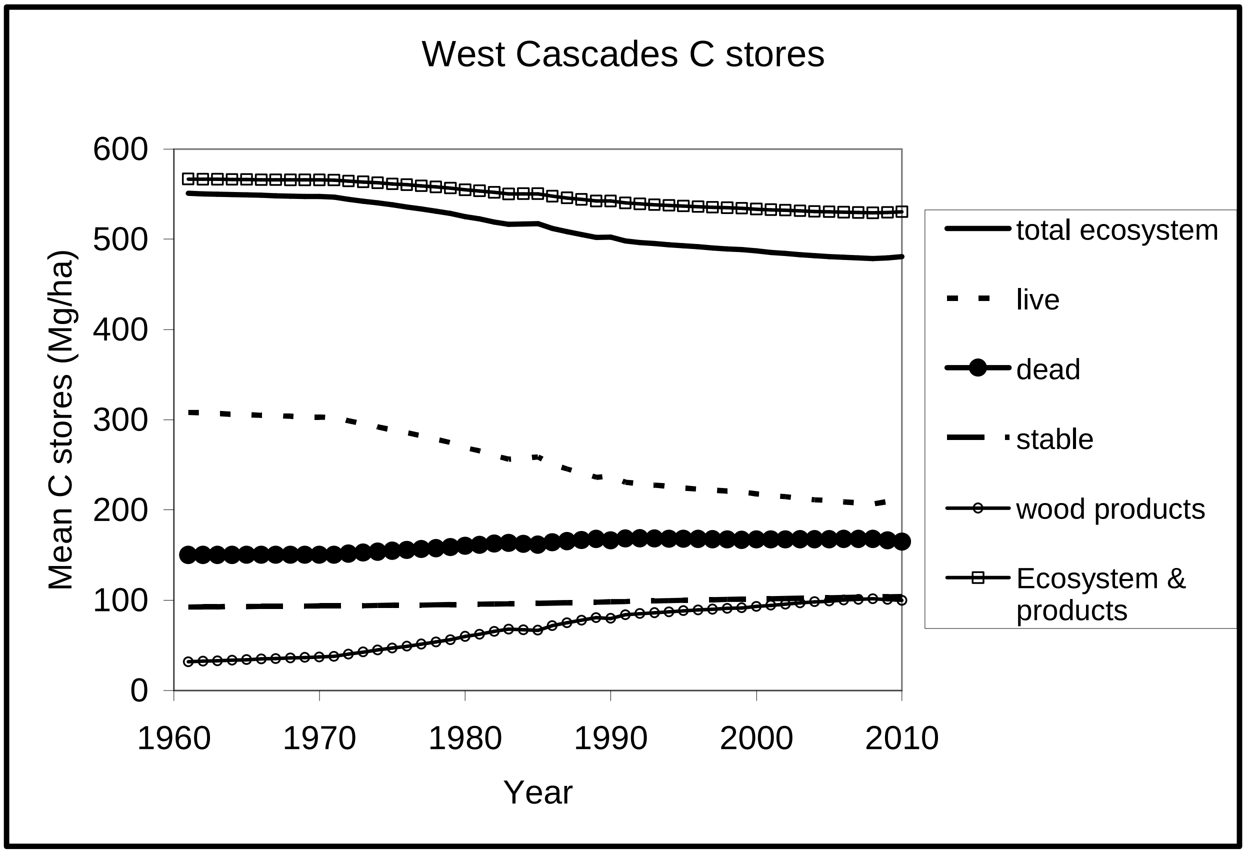

Figure 4. Change in carbon stores in western Cascade test area between 1960 and 2010.

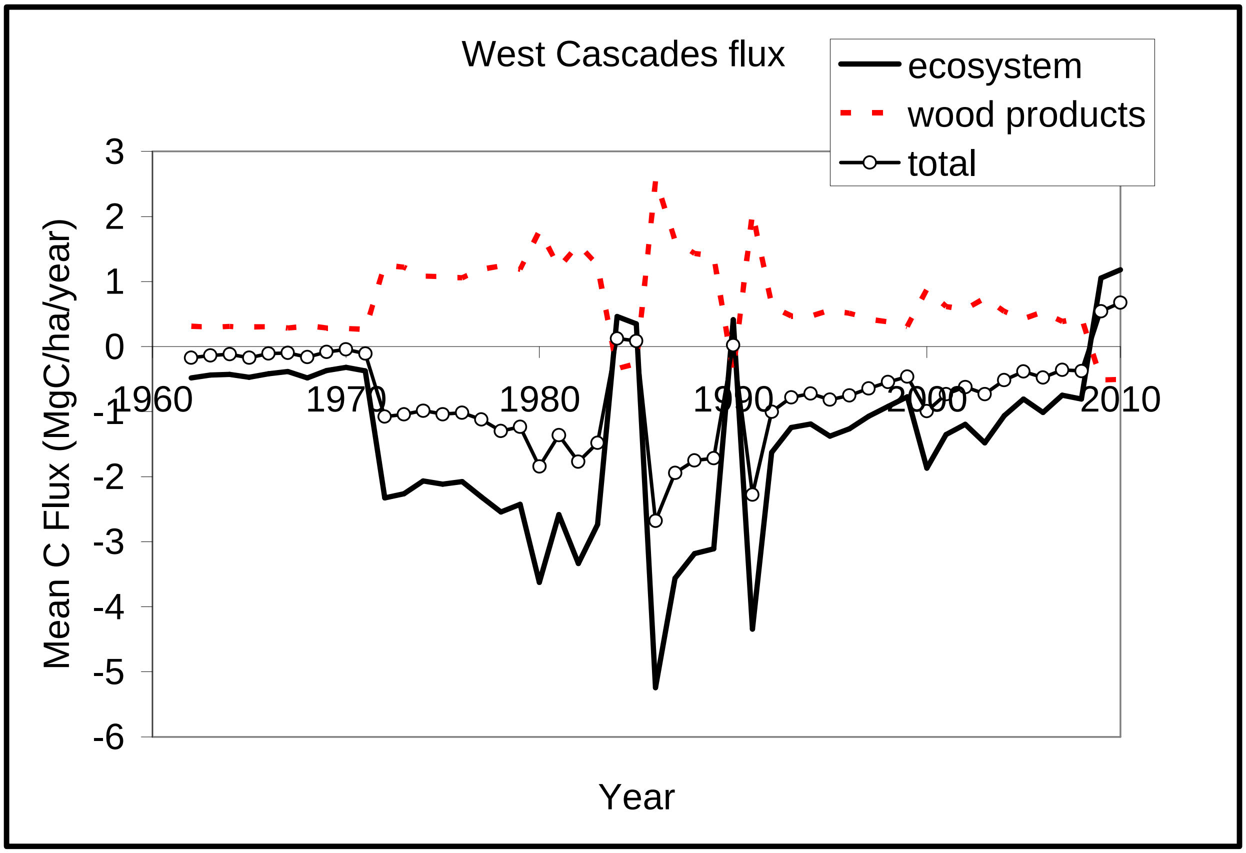

Figure 5. Change in average total carbon fluxes in western Cascade test area between 1960 and 2010.

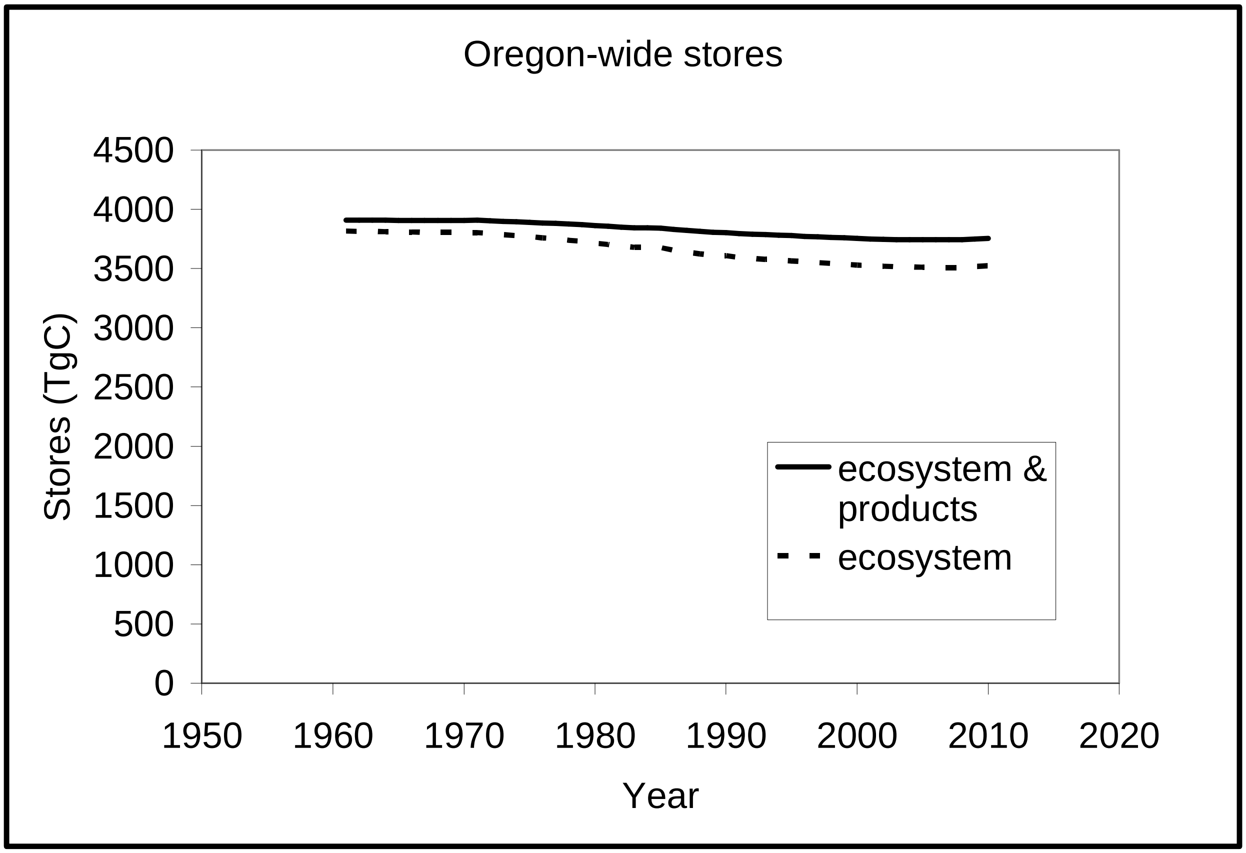

Figure 6. The estimated trend in carbon stores for all Oregon forest area between 1960 and 2010.

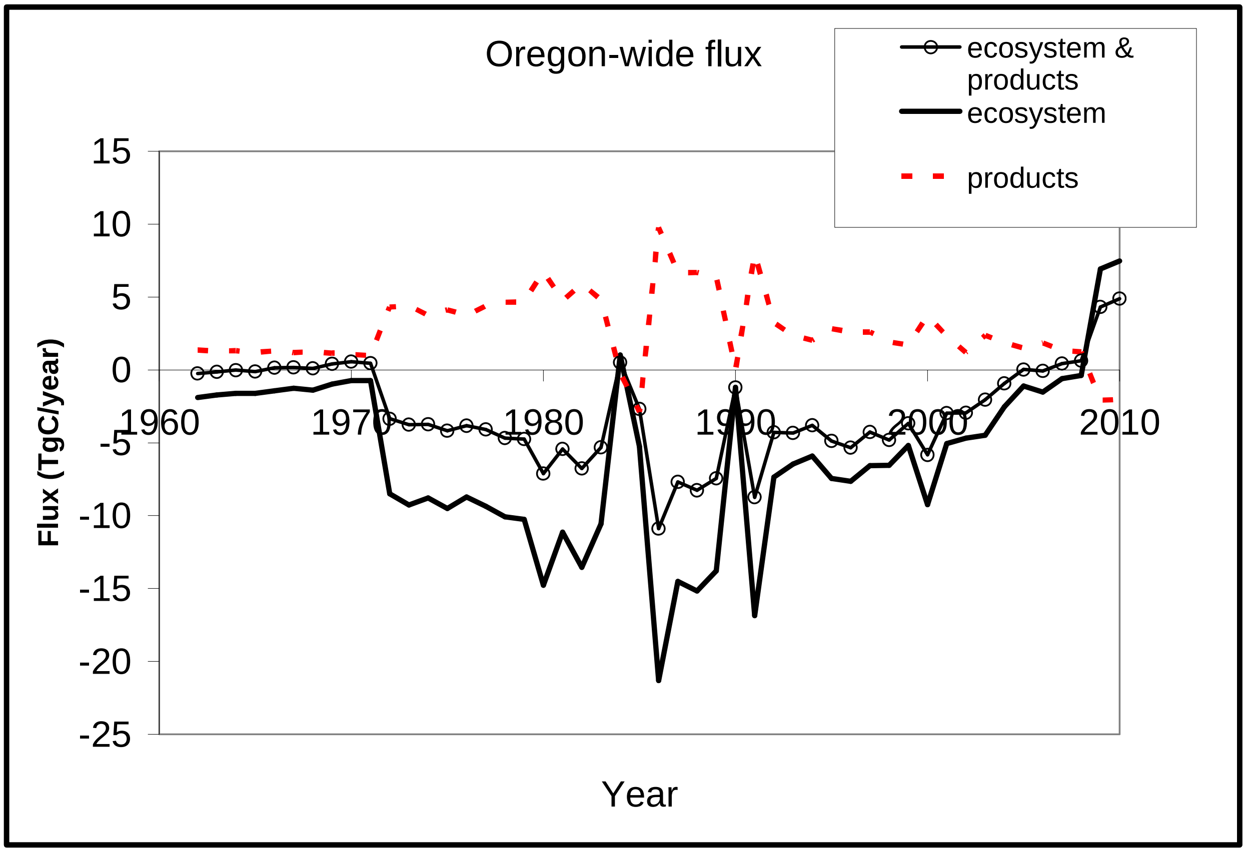

Figure 7. Estimated changes in carbon fluxes for Oregon forests from 1961-2010.

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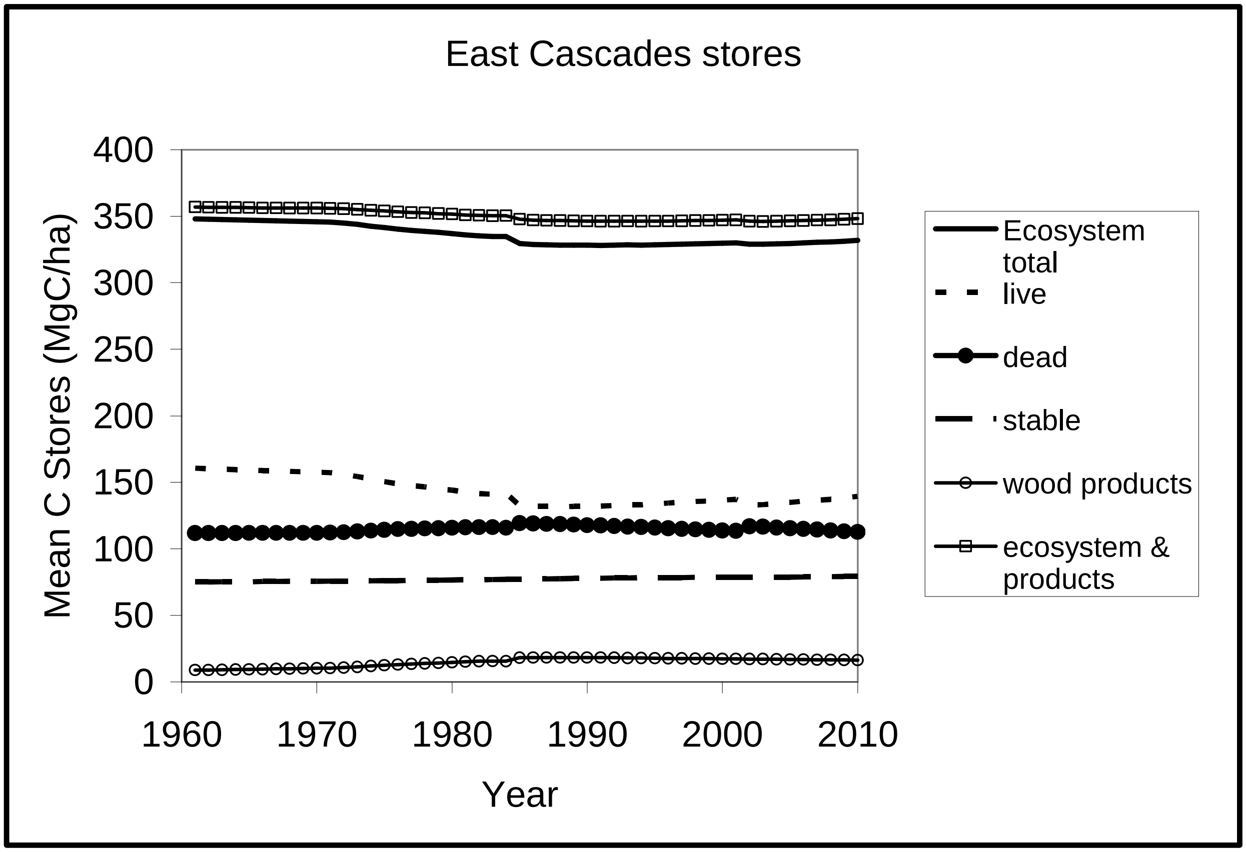
Appendix 1. Values of bole growth efficiency (BGE) assumed for the different forest regions in the middle elevation zone. BGE is the amount of bole organic matter produced per metric ton of foliage.

Region	BGE	Site Index for Douglas-fir
Western Cascades	0.59	medium 3
Eastern Cascades	0.42	medium 4
Klamath	0.38	low 4
Blue Mountains	0.29	medium 5

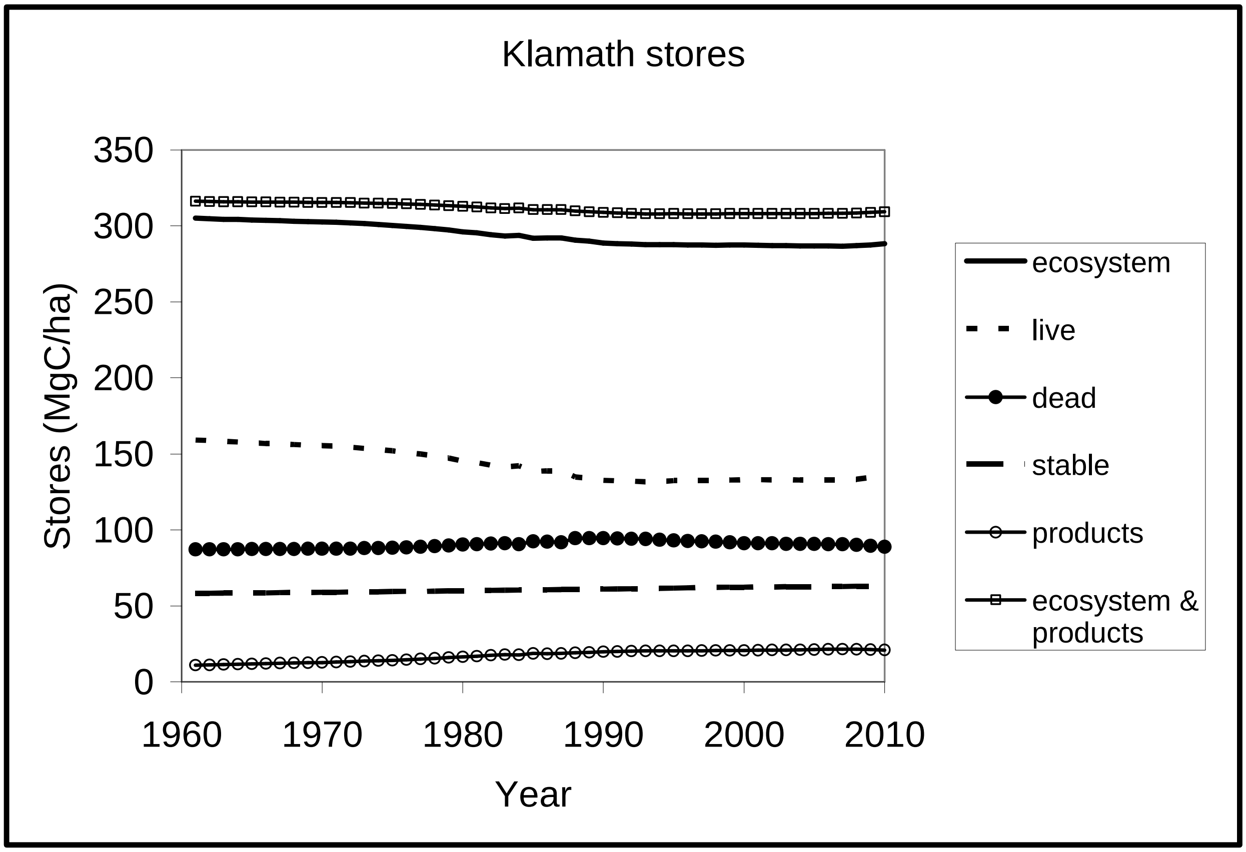
Appendix 2. Trees present in the seed zones for the four forest regions considered in this analysis

Region	Zone 1	Zone 2	Zone 3
West Cascades	Psme, Tshe	Psme, Tshe, Thpl	Abam, Abpr, Psme, Tshe
Klamath	Abco, Pila, Pipo Psme, Quga	Abco, Abma, Psme	Abco, Abma, Psme
East Cascades	Abgr, Pico, Pipo	Abgr, Cade, Pipo, Psme	Abam, Abpr, Pico, Tsme
Blue Mountains	Pipo, Psme	Abco, Pico, Psme	Abco, Abla, Pico, Pien Psme

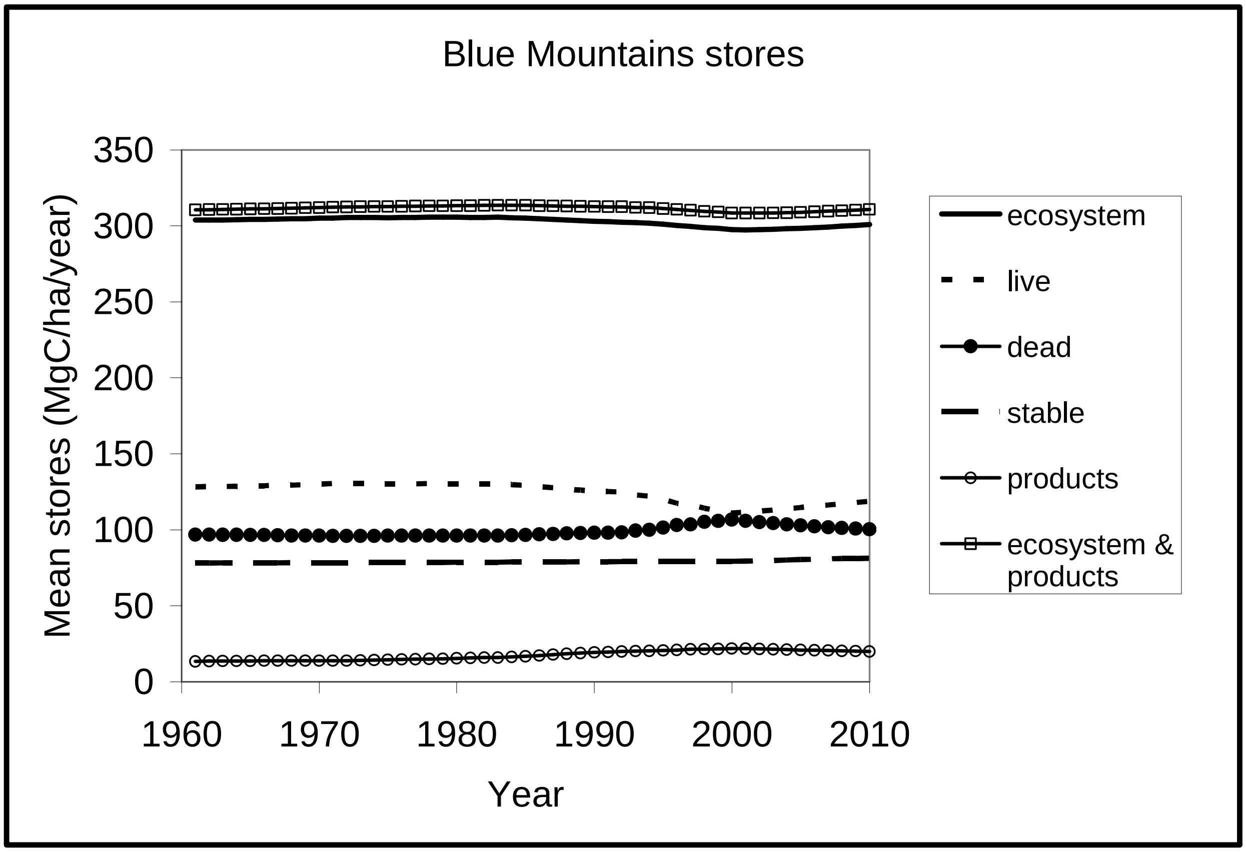
Appendix 3. Time trends in stores for the other forest regions (East Cascades, Klamath and Blue Mountains).



Carbon stores for the ecosystem and total forest sector in the East Cascade region have declined through the mid-1980’s. Since that time carbon stores for the ecosystem and total forest sector have gradually increased. Note that as with other regions, when live stores decline the dead and wood products stores increase and vice versa.

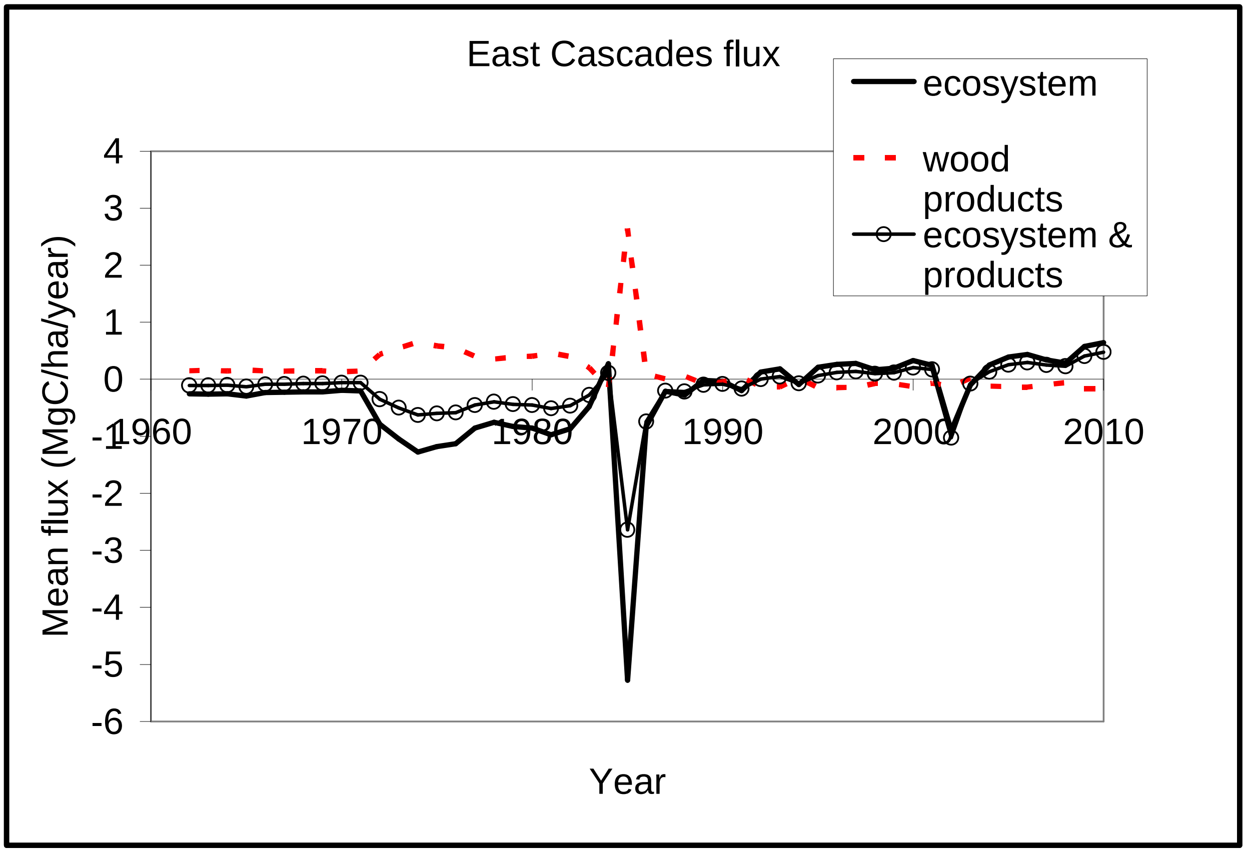


Forest sector carbon stores for the ecosystem and total forest sector in the Klamath region have slightly declined through the 1961-2008 period. Ecosystem carbon stores declined from 1961 to 1990 and seem to have remained relatively constant since then. Note that as with other regions, when live stores decline the dead and wood products stores increase and vice versa.

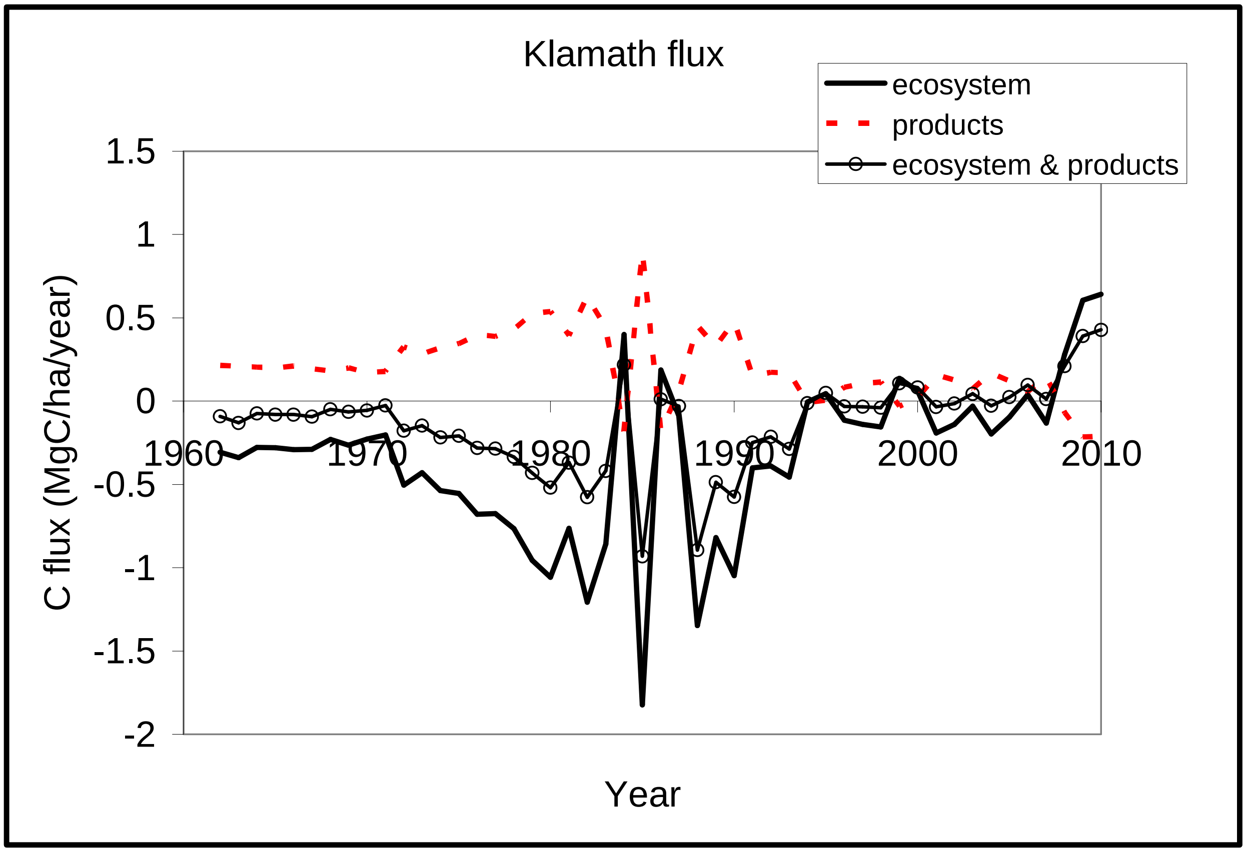


Carbon stores for the ecosystem and total forest sector in the Blue Mountain region have stayed relatively stable over the 1961-2008 period. Note that as with other regions, when live stores decline the dead and wood products stores increase and vice versa. An exception is the early 2000 period, when fire caused an increase in dead stores, but not wood products stores.

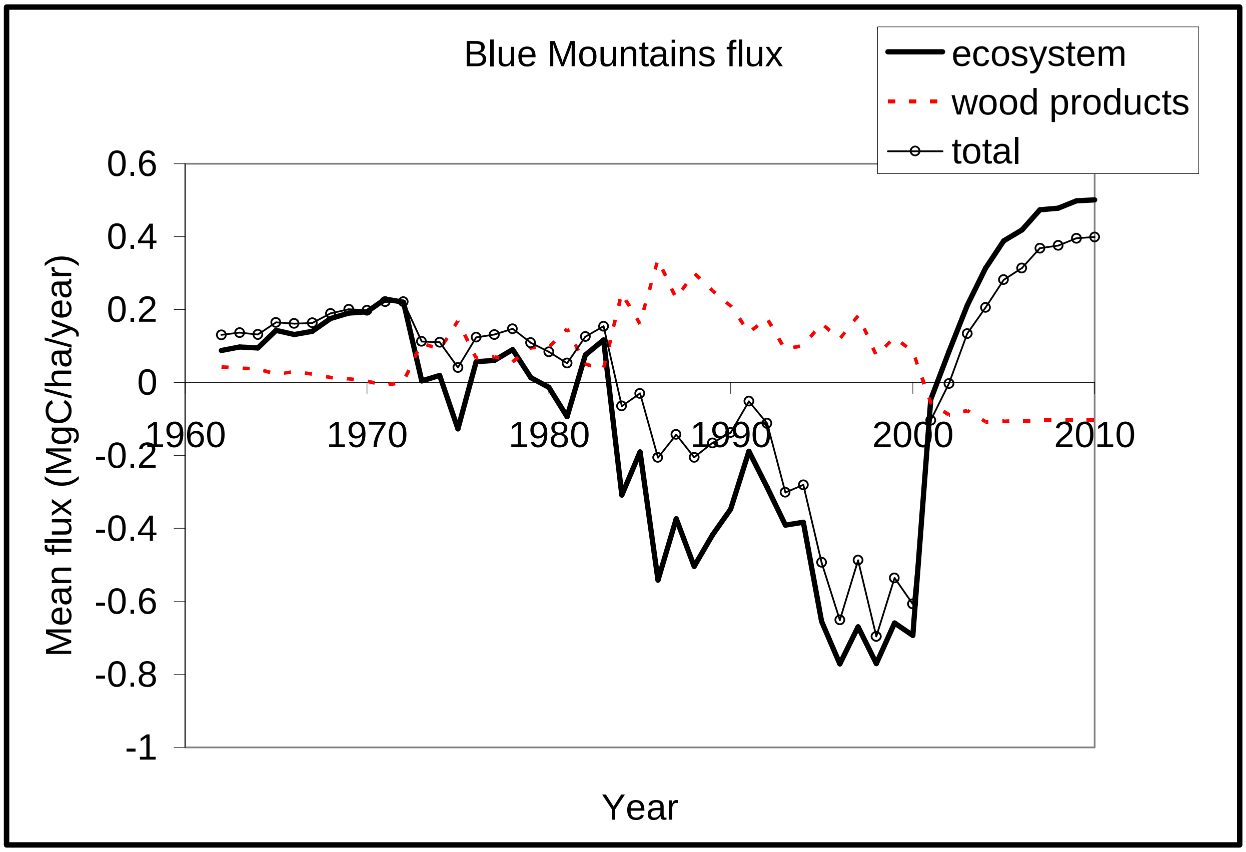
Appendix 4. Time trends in carbon fluxes for the other forest regions (east Cascades, Klamath and Blue Mountains).



Carbon fluxes for the ecosystem and total forest sector in the East Cascade region were generally negative (indicating a source to the atmosphere) until the early 1990’s. Since that time fluxes have generally been positive (indicating a sink from the atmosphere). The negative flux in 2002 was associated with wildfires. The negative spike in 1985 appears to be associated with a particularly high annual harvest that year.



Carbon fluxes for the ecosystem and total forest sector in the Klamath region were generally negative (indicating a source to the atmosphere) until 1995. Since 1995 it appears that this region has been in carbon balance, with some years negative (a source) and some years positive (a sink). The negative spike in 1985 appears to be associated with a particularly high annual harvest that year.



Carbon fluxes for the ecosystem and total forest sector in the Blue Mountain region were generally positive (indicating a sink from the atmosphere) until the early 1980's. During the 1980 to 2000 period, increased harvests caused a negative flux (indicating a source to the atmosphere). Since 2001 this landscape apparently has become a carbon sink, despite the net losses from wood products caused by a reduction in timber harvest.

Appendix 5. LandCarb Metadata Description

File Format

The spatial data generated by LandCarb is stored in single band raster files, in ERDAS IMAGINE image format. These images can be readily displayed and rendered in ArcMap.

Each image has a cell size of 100m x 100m (representing 1 hectare on the ground) and dimensions of 500 rows by 500 columns (representing 50km^2 on the ground).

There is one image for each combination of study site, year (1961 to 2010) and store/flux type (e.g. total mass, live flux). Images are grouped by study site into folders: WestCascades/, EastCascades/, Klamath/ and BlueMountains/.

File Naming Convention

File names include the store/flux type and year that the image represents. For example, LiveMass_1988c.img is the live mass for the year 1988. The ‘c’ suffix indicates that the values in the image represent carbon (as apposed to organic matter).

Study site is not an attribute of image file names, but rather is specified by the folder images are stored in.

Cell Values and Units of Measure

The cell values of the rasters represent either the store (mass) or flux at that location in the landscape. Values are stored as continuous floating points.

The stores files are: TotalMass, LiveMass, DeadMass, StableMass, HarvestMass and ForestProductMass. Units of measure are Mg C ha^{-1}.

The flux files are: TotalFlux, LiveFlux, DeadFlux, StableFlux and ForestProductFlux. Units of measure are Mg C ha^{-1} year^{-1}.

NoData Values

NoData values occur where water, settlement, roads and other non-productive forest areas exist in the landscape. Cells with NoData values were excluded from LandCarb modelling and subsequent analysis.