CORRIM: Phase II Final Report

Module K

Integrating Products, Emission Offsets, and Wildfire into Carbon Assessments of Inland Northwest Forests

As published in Wood and Fiber Science, CORRIM SPECIAL ISSUE, SECOND REPORT MARCH 2010 Vol. 42: 144-164

http://www.corrim.org/pubs/reports/2010/swst_vol42/144.pdf

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Acknowledgements

This research project would not have been possible without the financial support provided by the USDA Forest Service Forest Products Laboratory (04-CA-11111137-094), CORRIMs contributing university members, and the contributions of many companies. Special recognitions is extended to Larry Mason, and Jeffrey Comnick for their earlier work on the benefits of fuel removals to avoid fires and Bryce Stokes for his many reviews and persistent support. Any opinions, findings, conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of contributing entities.

Abstract

Life Cycle Inventories for the forest resources of the Inland West region of the Western US are impacted by the breadth of management strategies landowners use to meet their goals across differing site capabilities, forest types and species. Inputs and outputs from the forest resources and product carbon accounts are captured in the life cycle analysis (LCA) as reported in Oneil et al. (this issue). Here we provide a landscape level assessment of projected forest carbon driven by owner specific management intentions integrated through the useful life of the products produced and their end of life considerations. We show how using the forest as a sustainable pump to sequester the carbon, then harvesting and storing the carbon in long-lived products or using it as a bioenergy feedstock can substantially improve the carbon profile of forests growing in a high fire risk environment. Differences in management objective produce the largest differential in the potential for carbon sequestration in the forest and the mitigation of market induced emissions. We quantify how increasing fire risk predicted under climate change scenarios will reduce carbon storage in the forest and discuss the potential for treatments designed to reduce wildfire risks to reduce these carbon losses while also displacing fossil intensive products.

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Introduction

The life cycle analysis of harvest operations for the Inland West (Oneil et al. this issue) summarized and quantified expected yield and emission factors for the forest type and owner groups in the region based on a set of current and alternate management strategies. Here we provide detail on the underlying assumptions specific to each owner group and how management influences the carbon consequences both in the regions forests and the uses of biomass removed from the forest, i.e. a full accounting of carbon across all carbon pools impacted by management. In particular we focus on the substantial carbon differences between state and private forests and National Forests, both with and without assumptions about wildfire occurrence. In generating life cycle inventories of environmental burdens and life cycle assessments of their risks (LCI/LCA) for the forest resources in the four USA supply regions (Pacific Northwest (PNW), Southeast (SE), Northeast/North Central (NE/NC), and Inland West (IW)) CORRIM has consistently treated the forest under sustained management as carbon neutral in keeping with IPCC criteria (IPCC 2007). Under sustained management, biomass removed from the forest by either harvesting or decomposition is balanced by new growth. The IPCC (2007) guidelines also treat wildfire as carbon neutral. The carbon neutral assumption suggests that areas that are harvested or burned by wildfire regenerate to current stocking and there are no long term soil carbon losses effects. Here we examine the carbon consequences of management for private, state, and National Forest lands at current levels of management and under assumptions of more intensive management to address wildfire risk on national forests. We also examine the outcomes of the anticipated doubling of acreage burned in the region (McKenzie et al. 2004, Littell et al. 2009) under moderate climate change scenarios.

The forests of the Inland West are a complex mosaic of species mixes, habitat types, productivity classes, and ownerships. In order to compare results with life cycle analyses conducted for the Southeast and Pacific Northwest (Johnson et al. 2005), the complexity and diversity of the region was categorized into a relatively small number of homogeneous groups and treatment regimes using a number of simplifications. An overarching assumption relied on grouping forests according to an elevation gradient and moisture regime that captures many of the productivity and species composition differences in these forests. These groupings are commonly used for wide scale fire risk assessments as well as uniform treatment regime assessments. The groupings also capture a great deal of the variability in ownership pattern and the resulting management intensities on these ownerships. These broad groupings are identified as dry forests, including ponderosa pine, dry Douglas-fir and dry grand fir habitat types, moist forests, including moist Douglas-fir, grand fir, cedar-hemlock habitat types and the mixed conifer forest types, and cold forests, which include subalpine fir, spruce, larch, and lodgepole pine forests at high elevations. The high elevation forests are predominantly reserved from harvest or are under National Forest management.

Forestry operations may store carbon in the forest as one carbon pool and may also harvest new growth producing a stream of manufactured products that transfers forest carbon into buildings as a second carbon pool. If forest carbon is used as energy it can permanently offset the carbon emissions from fossil fuels as a third pool. Using wood products in buildings stores carbon for extended time periods but it may not be permanent after the end of building life. However as wood substitutes for fossil intensive products like steel and concrete, the displacement of emissions from these fossil intensive products is permanent, providing an important fourth forest related carbon pool (Perez Garcia et al.2005, Lippke and Edmonds 2006).

In the Inland West region, wildfire is the dominant natural disturbance regime (Agee 1993, Calkin et al.2005) though insect and disease outbreaks are common with mountain pine beetle (MPB) (*Dendroctonus ponderosae*) outbreaks creating extensive swaths of mortality in the recent past (Oneil 2006, Carroll et al. 2003, Gibson 2006). These disturbance agents collectively along with climate determine the range of forest stand structures, density and timber volume in the forest. At low elevations, wildfire, as often as every decade, had historically reduced stand density, leaving only large fire resistant trees in the overstory, whereas at high elevations less frequent wildfires typically caused complete stand replacement every 100 to 300 years (Agee 1993) often in concert with an insect outbreak. While salvage of mortality on private forests is common, salvage on National forests, and increasingly on state lands, is problematic because of the long planning horizons required to offer a timber sale contract on public lands (Bosworth 2002).

In recent years the extent and severity of wildfire is increasing, with a multiplicity of reasons identified as key drivers in these severe wildfires. Most prominent among the reasons are extreme weather conditions associated with climate change, and fire suppression and its effect on increasing fuel loads outside the historic range of variability for the region.

Climate impacts research on western forests indicates that even under optimistic warming scenarios we can expect at least a doubling of the fire rate for this region (Gedalof et al. 2005, McKenzie et al. 2004, Littell et al. 2009). The predictors for large fire years were all related to climate, suggesting that it is playing a critical role in the increasing extent and severity of wildfire. While these top down climate parameters control drying trends, ignition and rate of spread, ultimately fuel loading, which can be controlled by management, influences the behavior and outcome of wildfire events.

Bottom up controls on fire behavior and outcomes are mostly determined by the amount of fuel in the forest, which in a managed landscape is driven by the method and timing of harvest and fuel treatments. While pre-European stands had frequent understory burns allowing a stable overstory of a smaller number of large trees in particular for the dryer stands (Everett et al. 2008), with human population growth and a century of fire suppression, unmanaged stands today have become overly dense with excessive fuel loads. Now, when fires do occur they are generally stand replacing fires (Sampson et al.2001) instead of low severity or mixed severity fires that were a natural part of Inland West disturbance history and forest ecology (Agee 1993).

Historically wildfire did not burn every acre and burned some acres more than once in a short period to produce a mosaic of stand conditions. Camp et al. (1997) estimated that fire refugia would have historically occupied approximately 12% of the landscape. This suggests that 88% of the landscape burned at least once in a 100 year period given historical fire rates. The climate change predictions of a doubling of historic fire rate within the next few decades did not explicitly account for increasing fire severity, and consequent mortality associated with increasing fuel continuity from decades of fire suppression (Cromack et al. 2000, Sampson et al. 2001) and increasingly heavy fuel loads from large insect outbreaks (Oneil 2006) and other mortality events.

Methods

Stratification and Growth and Yield Modeling with FVS

The analysis used Forest Inventory and Analysis (FIA) (http://fia.fs.fed.us/) plots for Idaho, Montana, and eastern Washington covering all unreserved coniferous productive forests that generate more than 1.4 m^3/hectare/year (20 ft^3/acre/year) of volume. Plot data were segregated by owner group and major habitat type. The ownership categories used were state (S), private (P), and National Forest (NF). **Table 1** provides an acreage allocation of yield data by owner group averaged across the Inland West region based on FIA plots. FIA site quality metrics for the Inland West are given in cubic foot/acre/year growth potential rather than site index because the preponderance of mixed species forests and of the abundance of forests with multiple size class and age cohorts makes site index a less meaningful metric. For the same reasons, the Forest Vegetation Simulator (FVS) (Wykoff et al. 1982) variant used to estimate inventory growth and yield in the region uses habitat type rather than site index to identify differences in growth and yield across the landscape.

Table 1: Forest Yield allocation by Owner Group in the Inland West

Site Class		1	2	3	4	5	6	Total	Average Site Class
m3/ha/yr		>15.8	11.6-15.7	8.4-11.5	6.0-8.3	3.5-5.9	1.4-3.4		
Owner Group		Thousands of hectares and percent							
Private	Ha	3	78	421	986	1,790	1,716	4,994	4.93
	Percent	0.1%	1.6%	8.4%	19.8%	35.8%	34.4%	100.0%	
State	Ha	1	41	172	446	488	376	1,526	4.64
	Percent	0.1%	2.7%	11.3%	29.2%	32.0%	24.7%	100.0%	
NF	Ha	10	71	622	2,053	4,170	4,090	11,015	5.05
	Percent	0.1%	0.6%	5.6%	18.6%	37.9%	37.1%	100.0%	
Total by Site Class	Ha	14	190	1,214	3,485	6,448	6,183	17,534	4.98
	Percent	0.1%	1.1%	6.9%	19.9%	36.8%	35.3%	100.0%	

To be consistent with site quality estimates from the data and their projection in the growth model, the tree lists used to populate the stands represent the median inventory with respect to basal area and quadratic mean diameter for all plots segregated by owner and habitat type for all habitat types comprising more than 4% of the total area for each owner group. The habitat type/owner categories were then weighted according to the percentage of the land base they occupy to generate a total of 94 "stands" that were modeled for 30 unique habitat type/ownership categories. The stands were grouped into 10 portfolios across the region.
The portfolios were analyzed using the Landscape Management System (LMS) software (McCarter et al.1998) to simulate treatments for a 110 year time horizon with 100 years of data used for harvesting and economic analysis and the extra 10 years for generating fire risk assessments on the 100th year. The Landscape Management System used three FVS variants to model growth and yield: the FVS Inland Empire (IE) variant, the East Cascades (EC) variant, and the Blue Mountains (BM) variant.

Modeling Assumptions

Two cases were developed for the life cycle analysis: the base case representing current management and the alternate case representing an increase in management intensity within specific ownership classes. The base case reflects historical harvest rates by ownership and region applied across the habitat types according to their percentage on the land base. Base case harvest treatments were targeted to meet the average volumes harvested in the past 30 years by state and private owners. Beginning in 1994, National Forests show a marked decline in volume harvested across all three states in the study area relative to the 30 year average, therefore the base case for National Forests reflects harvest trends from 1999-2002. Specifically identified reserve acres on public lands are not included in the analysis, but those forest types where management would likely ensue under programs such as the Healthy Forest Initiative are included up to the acreage treated currently and all such acres are included in the alternate case analysis.

Base case management intensity for the owner groups was derived using survey information, assumptions about the location of small and large private land holdings, and historic harvest rates. Low intensity treatment regimes are those that might be used by some non-industrial private owners or government entities that are focused on establishing specific habitat conditions or addressing forest health issues. Data on private ownership classes suggests that approximately 53% of private forests are in ownerships less than 100 acres and that these smaller acreages are located closer to urban centers and at lower elevations (Rogers et al. 2009). We assumed these smaller acreages would include most of the dry forests and would be managed with a low intensity treatment regime. Medium intensity treatment regimes were used as the base case for private industrial and some non-industrial owners on moist and cold forests where the emphasis is most likely on timber revenue maximization. Regardless of survey information, cross validating the 30 year average harvest rates on private lands to yield from the median stand inventory weighted by habitat type suggests that current management on private forests is moderate to high intensity with very little merchantable volume remaining in any cutting cycle. This situation is more apparent in some sub-regions than others and has been explored in detail in the Future of Washington's Forests (Lippke et al. 2007, Eastin et al. 2007) for the eastern Washington portion of the study area.

The average harvest rates were allocated among the habitat type/ownership categories based on the percentage of land area occupied by each category with the assumption that across all ownerships they are 'harvesting the profile' of habitat types. As a result some regions were harvested intensely under the base case in order to meet target harvest volumes that had been historically removed from the regions. For habitat types that represent a large percentage of the land base, the inventory data was replicated with the total acres of all stands representing the total area of the habitat type. Even flow harvest and allocation between the management intensities was simulated by treating the replicated stands at different time intervals and intensities, while still maintaining the forest cover diversity and expected landscape level outputs across the region.

For the alternate case, we simulated an increase in the number of entries and the volume removed from private forests and increased fire risk reduction treatments on National Forest lands. While only the base case management intensity is likely for state forests as an assessment of long term state harvest trends suggests that volume removed from state lands has not responded to market trends, an analysis of potential incremental yield and carbon impacts were also completed as part of the alternate case.

Alternative strategies to maximize volume removed from private lands by increasing management intensity are possible, but the positive effect requires substantial increases in intensity in areas that have not historically been high timber producing regions. The potential for increased intensity on state lands is most pronounced, given the historic low intensity management and the substantial mature inventories that they currently carry. Maximizing volume through increased management intensities may not necessarily produce a greater net present value (NPV) using historic prices, as the higher volume and value tends to be generated later in the simulation period while investments in planting and stand tending occur early on in the simulation period. A second alternative to increase timber yield by fertilizing on moist Douglas-fir and grand fir forests in northern Idaho and northeastern Washington was assessed, but was not included in the alternate scenario as very few major industrial landowners have active fertilization programs.

For the alternate strategy all National Forest acres in dry forests, moist Douglas-fir and grand fir forests, and lodgepole pine forests were treated using restoration thinning strategies to reduce fire and insect risk while restoring a savanna-like overstory of taller trees similar to pre-European conditions. The resulting volume was then allocated across these forest types for the life cycle analysis. Treating all National Forest acres within these four habitat types roughly corresponds to thinning within low and mixed severity fire regime locations as well as managing the escalating impact of mountain pine beetle in lodgepole pine forests. Total treatable acres and volume were determined for the alternate case and then compared against acreage treated on National Forests during the current management era to arrive at a scale down factor for a current condition base case on National Forests. The National Forest treatments based on current harvest trends result in very low volume removals per cutting cycle. The opportunity to increase activity in fire restoration thinnings results in a five-fold increase in area treated in Idaho and Montana and a four-fold increase in eastern Washington.

The product volumes, emissions, and co-products associated with each of these regimes were weighted in proportion to the total volume removed from the acreage to derive estimates for an average acre under the base case assuming current practices and under the alternate case assuming more intensive practices and more federal lands actively managed to control fire risk. Comparisons between the base and alternate case assume that products and co-products are manufactured consistent with current technology and that markets for below economic breakeven biomass removals for bioenergy are not yet developed.

While the range of management practices used are only an approximation for the diversity of approaches used across the region, they define a logical range of management intensities and are sufficient to characterize the impact of current and potential future management practices. Results for the three owner specific treatment regimes define a set of outputs for the combination of management intensity and forest type groups. When weighted by the percentage of volume removed across the forest type/owner groups, the combined scenario represents an average carbon yield from the unreserved forest lands of the region.

Treatment Regimes

Simulated treatments included pre-commercial thinning, even-aged systems including clearcut, seedtree, and shelterwood, and uneven aged silviculture systems, which cut either the merchantable or non-merchantable materials depending on owner objectives. Decisions on the appropriate treatment were based on management objectives and existing stand conditions. There were multiple treatment paths within a given ownership/prescription class. For a given owner type, treatments regimes were generally consistent across habitat types within the dry, moist and cold forest types, but entry timing varied substantially by habitat type in response to highly variable growth rates.

To avoid harvests containing substantial pulp volumes, entries were timed so that stands would yield merchantable volume. Decision rules indicating merchantable volumes were based on minimum values in top height, volume and the equivalent of top diameter. In addition, treatments were designed to ensure that the residual stand contained sufficient overstory to meet statutory green tree retention targets. When a merchantable entry was simulated, both the volumes removed and remaining vary as a function of starting inventory which influenced how pole/sapling and understory layers were treated at the time of logging. Testing determined if understory and pole sapling layers were cultured as residual understory or removed because they lacked the capacity to respond to cultural treatments. The tests themselves assess the residual stand for species mix relative to site potential and habitat type, stocking levels, height to diameter ratios and release potential which is essentially a function of site quality and live crown ratio. For high elevation and wet forests on private lands even-aged harvest systems were simulated while leaving a minimum of four (4) trees per acre (TPA) (10 trees per hectare (TPH)) greater than ten (10) inches (25 cm) in diameter at breast height (DBH) to meet statutory requirements for green retention trees.

On private dry forests seed tree and/or shelterwood regimes were simulated to re-establish the next crop, but with no retention of the dominant cohort except for statutory requirements for green retention trees. On private moist forests, regular entries removed merchantable volume, with only minimal stand improvements. Alternative strategies in moist forests also depend on regular stand entries, but there is an aggressive focus on re-establishment and stand improvement such that more fill planting and removal of advance regeneration occurs. Harvests on state forests assumed similar treatment regimes as those for private forests except that more and larger leave trees were retained as part of a statutory requirement, a seed tree system, or as a shelterwood, including retention of the largest trees in the stand. On state and private forests, simulations included regeneration with seral species in the range of 620-865 TPH (250-350 TPA) with additional natural regeneration added to reflect the species diversity in the overstory. Seral species included ponderosa pine, larch, and white pine depending on the habitat type.

For National Forests we assumed that thinning from below was standard with trees removed up to a diameter limit of 12 inches (30 cm) DBH. After that limit was reached, on pine stands at risk for mountain pine beetle outbreak, a further removal to a basal area of 60 square feet/acre (14 m^2/ha) was also applied. No planting was assumed, but natural regeneration was included in the simulations with species compositions based on forest type, overstory species composition, and habitat type.

Harvesting

Harvest volume was separated into sawlog, hewsaw (a small sawlog typically less than 18 cm (7 inches) in diameter), and pulp log dimensions. Sawlog and hewsaw are merchantable, but direct delivery of pulp logs is contingent on cyclical pulp markets. For that reason, direct delivery of pulp from the woods was not assumed to represent a significant part of the volume though some pulp quality material would be brought in as part of the larger merchantable log. There was a higher percentage of pulp quality material produced from understory thinning on National Forest lands which affected the commercial volume removed from the woods and the volume left on site after harvest. Because of existing stand conditions and even flow constraints, there are three decades of the simulation for the maximum volume alternative where volume per entry is less than the base case. This reduced volume is a result of early stand tending and conversion to seral species which produce much higher volumes later in the simulation period.

Aggregating Simulations

Once the 94 stands were treated and grown in their respective habitat types, harvest volumes produced from each management activity within a treatment regime were summarized across the three variants and states to represent a regional average for each forest category. Results were initially aggregated into the three general combinations of site quality identified by the forest type designation (dry, moist, and cold) and ownership category (state, private, and National Forest). The small percentage of acres in state and private cold forests and state dry forests combined with uniformity of yield values resulted in further aggregation into three categories: state and private dry forests, state and private moist and cold forests, and National Forests. These combinations reflect the range of management intensities common to state and private lands as well as capturing the limited management activity occurring on National Forests at this time.

For the alternate case, the state and private dry forests were disaggregated because of the lack of response noted on state lands with respect to changing policies and market forces. Private forests had a maximum volume alternative applied to the extent possible given current harvest trends. The alternative for the National Forests simulated treatments to managing fire risk on all dry forests, moist Douglas-fir and grand fir forests, and harvests in lodgepole pine forests to control the mountain pine beetle. The alternate regime for National Forests assumed that continued management to reduce fire and insect risks would occur despite lack of financial incentive after the first entry. The alternative strategies were then grouped into three categories: private maximum volume, National Forest fire and insect risk mitigation, and state moderate intensity treatment regimes.

Harvest volume and carbon removed, and left on site, for the two cases and owner groups are provided in Oneil et al. (this issue). To simplify the complexity of the various silvicultural pathways, the yield summary generated estimates of cumulative volume harvested across types for both the base and alternate case standardized to a 75 year rotation. This analysis shows the carbon accumulation per decade for the 110 year period reflecting trends in forest carbon sequestration and wood utilization over time assuming continued and ongoing active management and silvicultural investment.

For the National forests, alternate case volume estimates assume a 30-40 year re-entry period. It was assumed that each initial entry generated enough merchantable volume to haul material to the processing facility. In order to maintain the benefit of thinning treatments with respect to fire safety, additional treatments were required on a 30-40 return interval. For the alternate case, these average yield figures were applied to the acres identified as part of a healthy forest restoration initiative. To calculate a base case, 20% of the alternate case was apportioned to initial treatments in dry forests first and then to initial treatments in moist forests after which the estimated current National Forest accomplishments would be completed. This front end loading of treatment regimes generates irregular patterns in deadwood accumulations in the forest for the base case.

Depending on the growth of regeneration and the overstory, the second and subsequent entries in the National Forest restoration thinning treatments typically did not yield much merchantable volume therefore the carbon accounting data includes estimates of harvest inputs, but no hauling costs as there is insufficient wood to warrant removal to the mill. Since the impact of treatments assume no fire, insect, or disease impacts they provide only a static assessment of potential carbon storage. The increasing forest inventory suggests that fire and insect risks would also be increasing and would therefore likely provide a feedback mechanism that would cap the inventory that could be carried. We explore that consequence under the fire impact assessment.

Landscape Carbon Estimates

For the forest, an average per hectare carbon value was generated using the protocols outlined in Oneil et al. (this issue). Forest pools include the live trees and all their components, the dead trees which decompose at species specific rates as defined by Aber and Melillo (1991), and inputs and decay of forest litter. Soil carbon is not explicitly tracked in the carbon charts as research suggests that on average there is little change in soil carbon under active forest management (Johnson and Curtis 2001, ter-Mikaelian 2008), even when transitioning from old-growth to second growth conditions (Fredeen et al. 2005) unless there is application of urea fertilizer (Adams et al.2005, Canary et al. 2001) which tended to increase soil carbon accumulations. Utilization of woody debris as a bioenergy source material may alter the assumption of no net soil carbon change (Johnson and Curtis 2001), but removal of waste materials was not explicitly included in this analysis. Fire may also reduce soil carbon, either from volatilization during the burn (Bormann et al.2008), or by erosion in the immediate period following vegetation loss (Baird et al. 1999, Helvey et al. 1985).

Regional milling surveys (Puettman and others this issue) were used to allocate the log into long, medium, and short-lived uses. End of life for long lived product uses were estimated to be 80 years (Winistorfer et al. 2005, Perez-Garcia et al. 2005) with no recovery or land fill sequestration of embodied carbon accounted for in the analysis as a tutorial simplification. Displacement carbon refers to reduction in fossil fuel energy equivalent by burning woody biomass as hogfuel in place of natural gas for heating and processing energy needs (Puettmann and Wilson 2005). Displacement carbon was calculated based on energy equivalents and the amount of hog-fuel and mill residuals used to displace fossil fuels that would be otherwise used in milling processes for Inland West mills. Substitution carbon in CORRIM's initial research was derived from the differential between the carbon footprint of a wood framed house and their dominant concrete frame substitutes (Perez-Garcia et al.2005). The substitution parameter varies by material end use and will likely increase with an increasing price of fossil fuel or value of carbon as this would motivate greater use of relatively lower cost wood in applications where fossil fuel costs are highest. Sathre and O'Connor (2009) developed a meta-analysis of all substitution studies in the literature and concluded the average substitution rate was 2.0 displaced units of carbon for each unit of carbon in the wood used. We use this parameter to identify the carbon benefit in substitution for that portion of the wood basket that is milled into solid wood products although it is 20% lower than the substitution derived in prior CORRIM studies for wood substitution for concrete walls as the dominant form of substitution.

Simulations first generated estimates of carbon production in the forest, product, displacement, and substitution pools under the assumption that no timber volume was lost to wildfire, insects or disease during the simulation period. A secondary analysis was undertaken on National Forests to assess what impact wildfire might have on carbon emissions and sequestration over the simulation period.

Fire Risk

We model the impact on forest carbon of including the historic wildfire rate and the impact of a predicted doubling under climate change scenarios, as compared to the estimate of forest carbon that would remain given the current management regime on National Forest lands under the no wildfire assumption. Estimates of wildfire impacts use several simplifying assumptions. First, area burned is distributed across the landscape so that the carbon in the average hectare, as represented in the graphs, is reduced proportionately to the area affected. This assumption may underestimate carbon emissions and impacts as stands with higher fuel loads and correspondingly higher carbon equivalents tend to have a higher fire risk and therefore may be disproportionately represented in the area burned. Second, we assume that all fires are stand replacing events which will over-estimate the carbon emissions and increase in the dead pools, potentially balancing out the first assumption. We use variables from Wiedenmyer et al. (2006) to estimate wildfire emissions including average fuel consumption of 30% for the woody materials and 90% for the litter. Carbon equivalents (CE) for the average emissions profiles for the five Global Land Cover (GLC) classes in the region were estimated at 675 kg CE/ t biomass burned. These CE values reflect the greenhouse gas (GHG) impact of the carbon dioxide, methane, nitrous oxide components, and volatile organic chemicals that are emitted during a wildfire. Because the non-CO_2 compounds have higher global warming potentials than CO_2, the CE is higher than the total carbon content of the biomass.

Results

Changes in Landscape level Carbon Pools over Time

Results are provided in a series of charts showing the average per hectare (ha) value for all stands in the owner group. As such the carbon pools represent a landscape level assessment of the carbon in the forest and other pools (when treatment occurs) for the composite stand represented by the aggregated FIA data for that owner group. As downed wood inventories were not consistently available across the entire dataset, estimates of downed wood for the initial period were not calculated, but are included when harvest or wildfire occurs.

Our base case for the state and private commercial forests simulated management at a sustainable harvest rate in that harvest removals were generally equal to new growth less natural mortality. The forest is composed of a range of stands at every age and while stands are continually harvested the overall average inventory remains relatively stable. Since every carbon pool is simulated dynamically to grow or die and decompose or reflect harvest removals, the results demonstrate sustainability and carbon neutrality, it is not assumed. Figure 1 gives the weighted average for all acres and all projected harvest volumes for the state and private acres in the base case. Decreases in forest carbon in any particular time period reflect shortfalls in available inventory relative to historic harvest rates. Increases in forest carbon indicate that projected growth exceeds historic harvest rates for the region in question during that period of time. Forest carbon (not including soil carbon or estimates of large woody debris at the beginning of the simulation) begins at 44 tonnes per hectare (t/ha) and increases to about 74 t/ha after 100 years of active management with an average of 59 t/ha (26.3 tons/acre) in the stem, roots, crown, litter, and slash. The increase reflects a modest cycle introduced by the uneven aged inventory and some volume increase in regulatory set asides. The landscape level analysis across state and private acres in the Inland West illustrates that under current management strategies there is the potential to increase carbon stored in the forest if harvest continues at current rates.

While the carbon in the forest remains relatively stable, the carbon in products continues to grow with each year's harvest when even a portion of the harvested log is used in long-lived applications. Figure 2 shows the carbon storage, for both the forest and off-site pools, that would ensue under current marketing and infrastructure conditions from the sustainable harvest of Inland West state and private forests under the base case. Figure 2 shows that even with increased sequestration in the forest, there is substantial opportunity to accumulate carbon in products, displacement (using wood residues for energy instead of fossil fuels) and substitution (using wood products instead of fossil intensive products) as a result of harvesting trees for products even when accounting for the energy costs of producing products. Whereas average forest carbon for the simulation period was 59 t/ha, accounting for the remaining pools (net of their emissions) increases the average carbon stored to 186 t/ha under this management scenario and for this portion of the forestlands. This threefold increase in carbon more accurately reflects the potential of well managed forests to contribute positively toward offsetting global warming trends. Most of the increase derives from the accumulation of long-lived products, displacement of fossil fuels directly, and displacement of emissions by substituting for fossil intensive products. While the carbon stored in the forest remains fairly stable for this treatment regime, the carbon transferred from the forests that displace fossil intensive products continues to grow. Energy used to grow, harvest, transport, and process the logs into wood products is identified as manufacturing and harvest emissions in Figure 2 and subsequent charts that show all carbon pools. The Life Cycle Inventory indicates that these emissions are minor relative to the carbon stored in products, displaced by using wood energy rather than fossil energy in manufacturing, and in substitution for fossil intensive products.

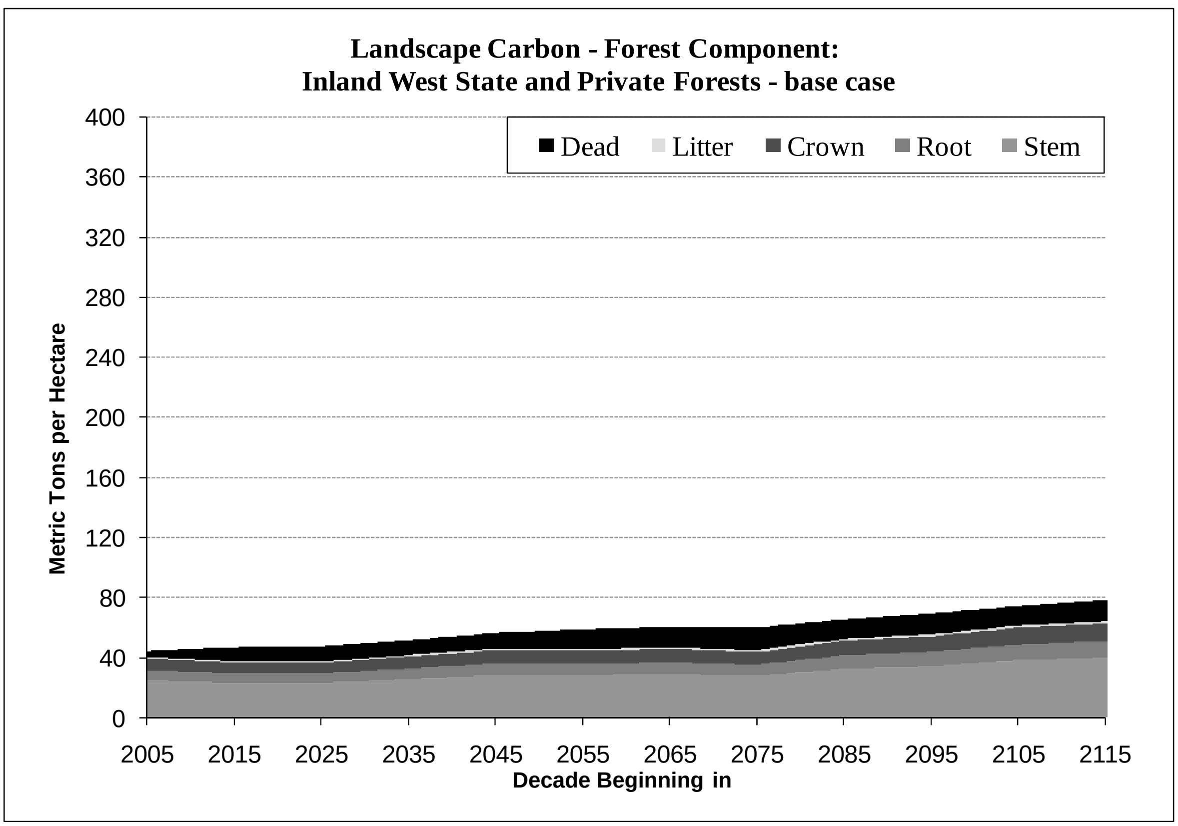

Figure 1: Weighted average of Inland West state and private forest carbon pools – base case

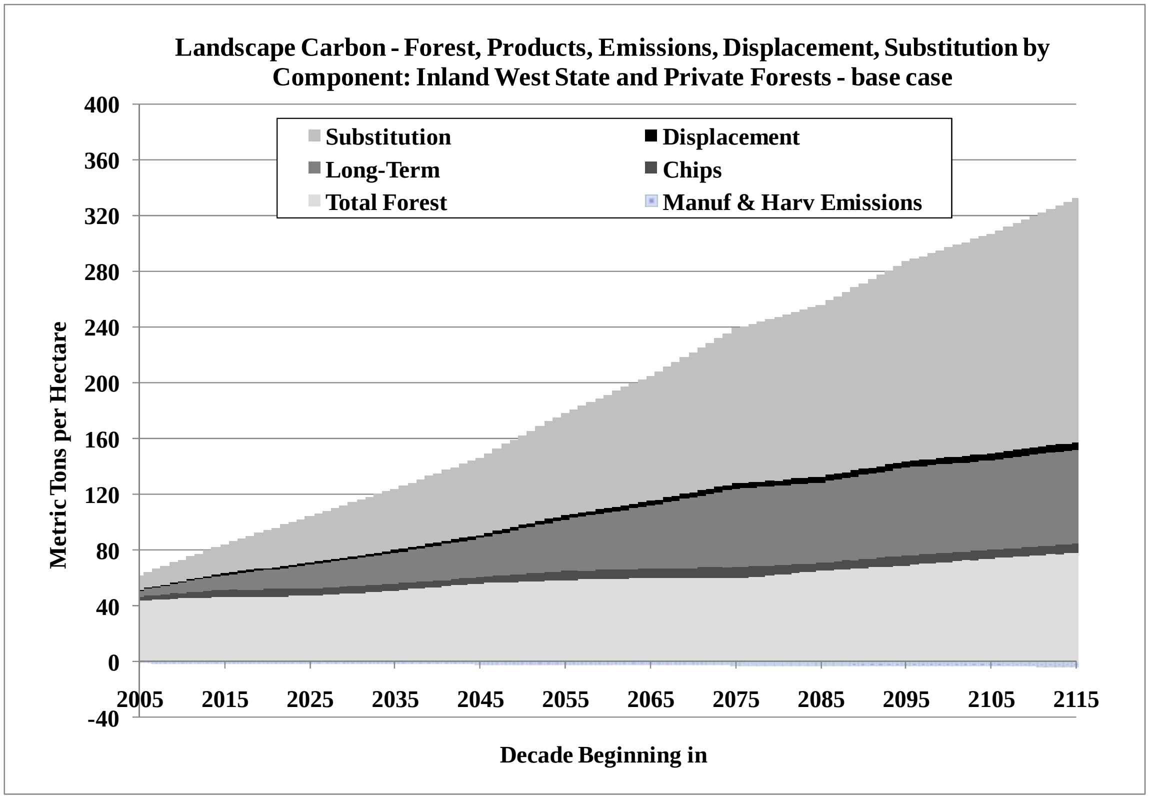

Figure 2: Weighted average of Inland West state and private all carbon pools – base case

The harvest level assumed for the simulation was based on the average harvest rate over the past 30 years, suggesting that while there is no retroactive reporting of the non-forest carbon pools from earlier harvests, we could expect that about 75 t/ha have already been sequestered in offsite uses by the beginning of the simulation (2005). Even disregarding the carbon that was stored from harvest in the prior 30 years of harvest, this full carbon accounting shows that the carbon stored in products, displacement, and substitution less emissions from manufacturing and harvesting is equal to that stored in the forest by the end of the first decade. Substitution alone equals carbon stored in the forest by year 30 and by year 75, the product pool contains as much carbon as the forest even accounting for the 35% increase in carbon stored in the forest which is made possible by continued investment in forest management paid for through sale of the harvested products. By 100 years the 294 tons of carbon stored in off-site pools is 4 times greater than the carbon stored in the forest under this base case scenario for state and private forests of the Inland West. Despite the relatively low quality growing sites in the Inland West, increases in the growth of carbon in long-lived products demonstrates availability of products at a faster rate than their elimination rate at the end of their useful life. While the long lived products have lives modestly less than 100 years and the short lived products do not result in significant accumulation of carbon from one rotation to the next, from the perspective of managing a unit of land, the carbon pools are better than permanent, increasing sustainably at 5.5 t CE/ha/yr.

Figure 3 demonstrates the weighted average of carbon sinks and sources on all state and private lands for the Inland West under the alternate case were these forests to be managed more intensively. There is little potential gain in carbon storage under more intensive management suggesting that without increases in forest productivity or gains from biomass-to-energy initiatives, the base case is near a maximum for carbon sequestration. A sensitivity analysis of the potential for increasing forest productivity using fertilization (not shown) suggested that substantial gains would only accrue if large areas were fertilized to increase productivity and shorten rotations. As this option was not considered economically likely, it was not included in the landscape level modeling.

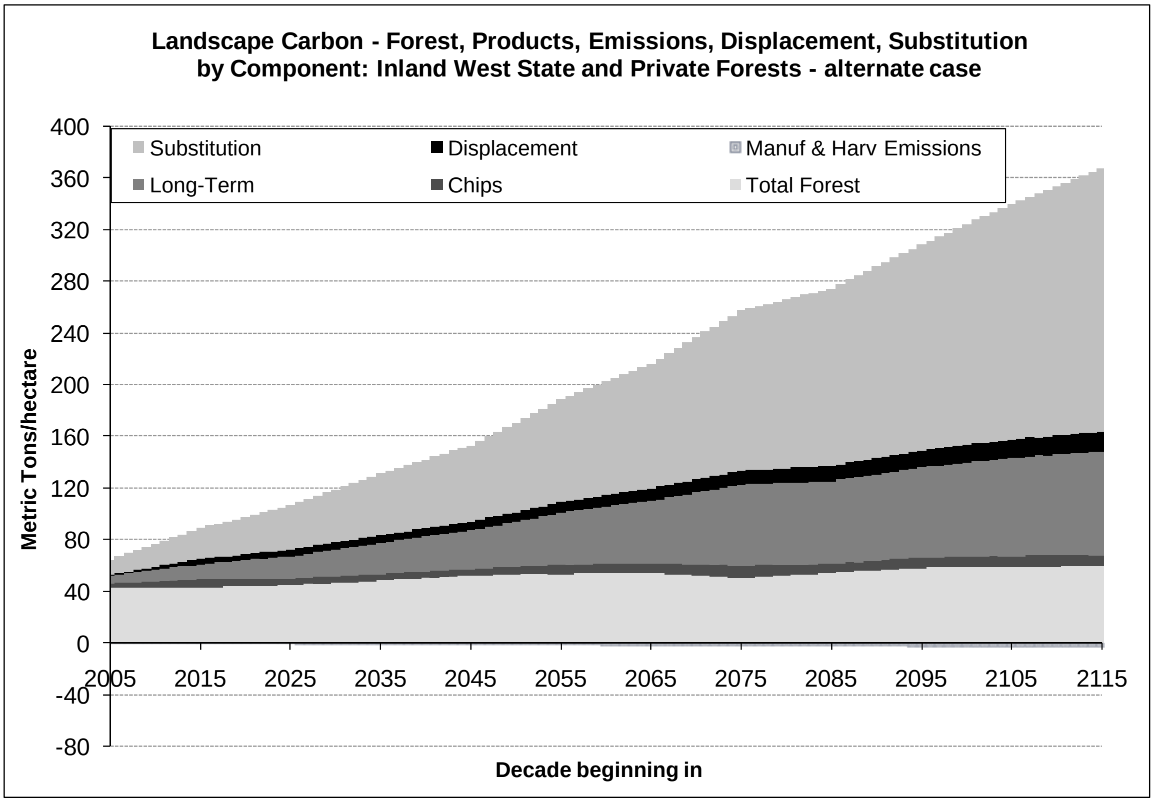

Figure 3: Weighted average of all state and private forests – alternate case

Carbon pools for National Forests are shown for current management (base case) in Figure 4 and the alternate case in Figure 5 assuming no fire or other disturbances. Treatment alternatives for National Forests are more complex as they are managed for forest health improvement and fire risk reduction rather than for maximum sustained yield or revenue. In both cases the assumption of thin from below treatments with removal of few merchantable products, applied to the current treated acreage (base case) and all acres in habitat types likely to be treated for fire safety (alternate case) demonstrates the leverage and importance from a carbon standpoint of the long term product pool and its substitution benefit. Because the thin from below treatments generated few large sawlogs and over 45% pulpwood, harvests generated few long-lived products with corresponding small long-term product and substitution pools. The fluctuation in the dead-wood component results from rapid implementation of the first thinning in the treatment regime followed by a second entry with fewer residuals. While thinning all acres in low and mixed severity fire regime habitat types in the National Forests (Figure 5) reduces the fire risk on treated stands while transferring more of the excess inventory into product carbon pools, the wood product, displacement and substitution pools only reach 200 t/ha with most of that still in the forest as compared to 320 t/ha from sustainable harvests on state and private lands. The National Forest estimate in particular is likely quite optimistic because the inventory is still growing with an increasing fire risk. Since the carbon across all pools with increased thinning (figure 5) is not significantly different than the potential carbon with less thinning (figure 4) the benefits of increased thinning will largely be in the reduced losses likely from a climate related increase in fire rate.

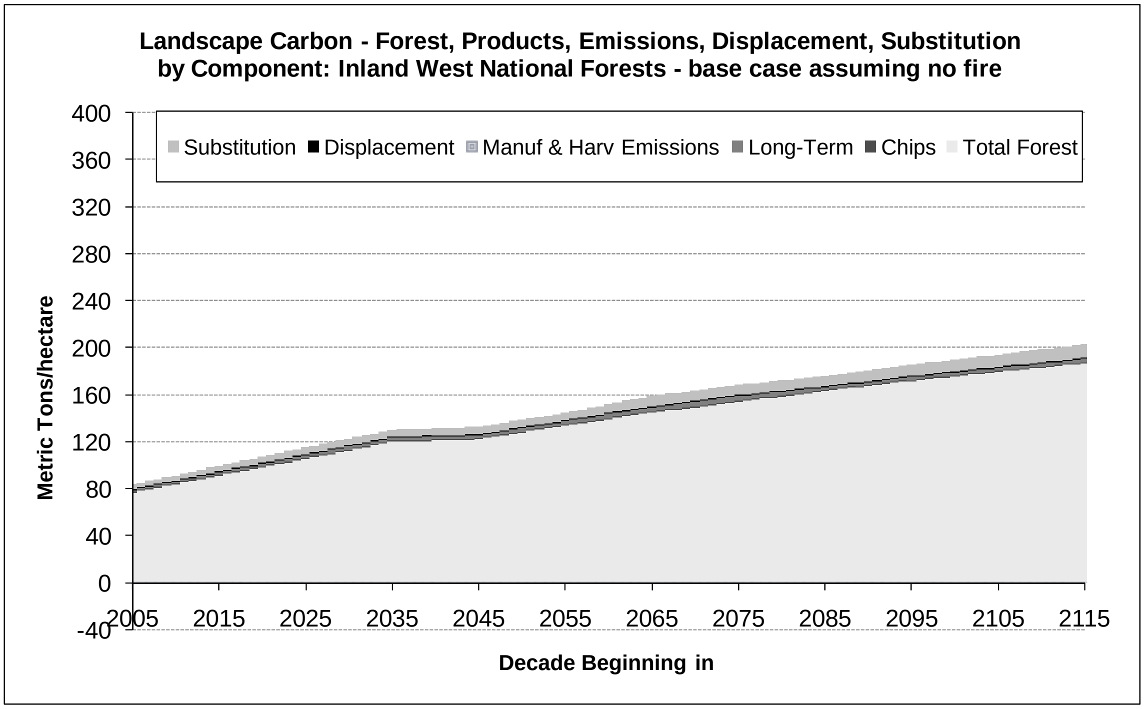

Figure 4: Weighted average of Inland West National Forests – base case

Stands on National Forests carry much higher inventories than for private forests given their history of minimal harvesting, fire suppression over many decades, and the higher volumes present at higher elevations. At the beginning of the simulation, the average hectare of National Forests carries approximately 75% more carbon in the standing biomass than the average hectare of private and state lands (Figure 4 and Table 2). While fire rates have already increased and are expected to increase even more, under the assumption of no fire losses for 100 years National Forests could potentially carry 140% more carbon in standing inventory than sustainably managed state and private lands. Despite the larger potential carbon storage on National Forests, overall carbon stored in all pools after 100 years is 53% higher from state and private lands under the base case and averages 26% higher over the entire 110 year period when all pools are considered.

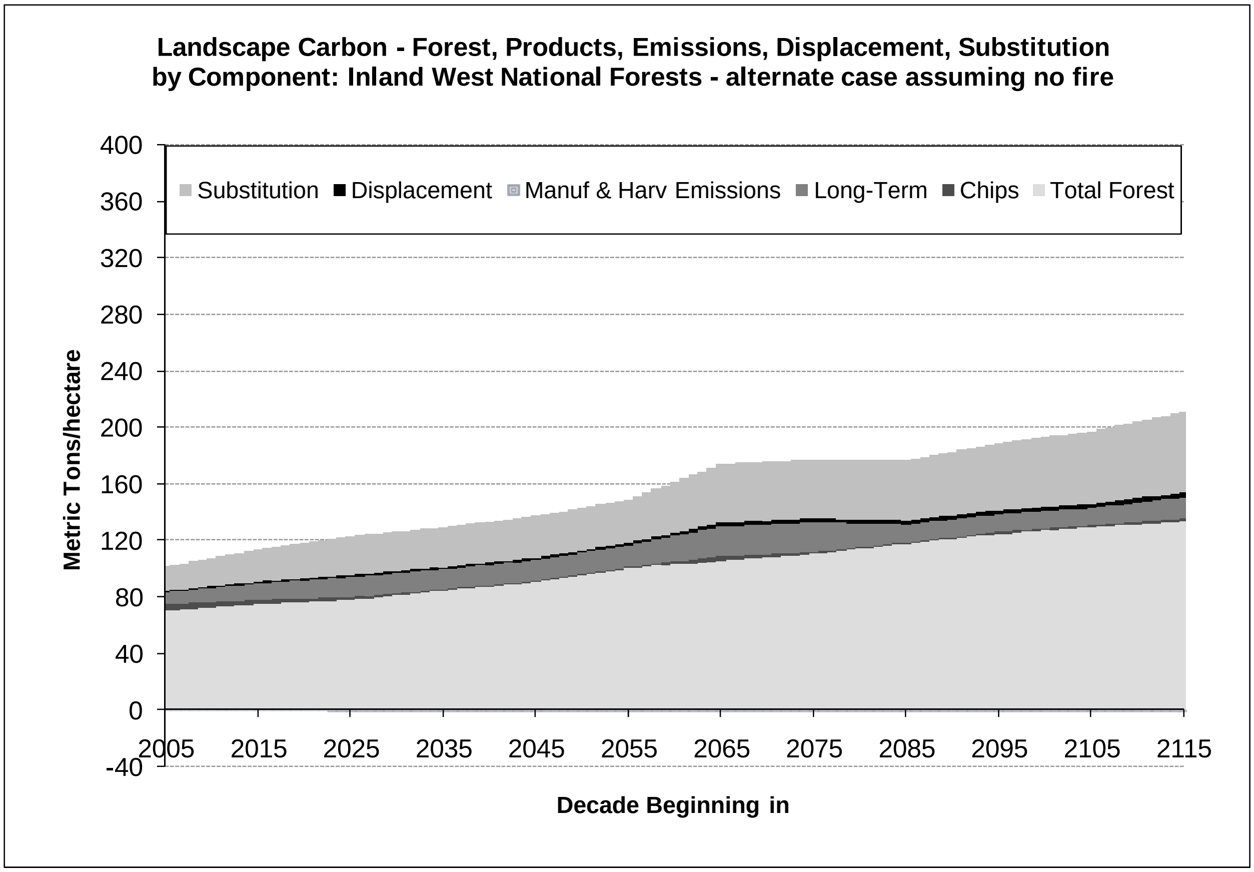

Figure 5: Weighted average of Inland West National Forests with increased thinning

By 100 years the active management on private and state forests has sequestered or avoided emissions of approximately 300 t/ha of carbon over the approximately 6.5 million ha of forest land in this category for a net effect of approximately 1 billion t of carbon removed from the atmosphere (Figure 6). On National Forests, carbon sequestration and avoided emissions is 192 t/ha (Figure 6) over the 11 million ha of unreserved forest land in this category for a net storage of 2.1 billion t of carbon. In both cases the assumption is that wildfires do not occur or are salvaged if they do occur, the areas burned are reforested in a timely manner, and that no net loss of forest productivity or soil carbon ensues from wildfire.

The growth model predicts a doubling of standing carbon over 100 years under National Forest management regimes. The increase in fuel loads will produce a higher risk of stand replacing fire events, even with constant ignition sources and climate conditions.

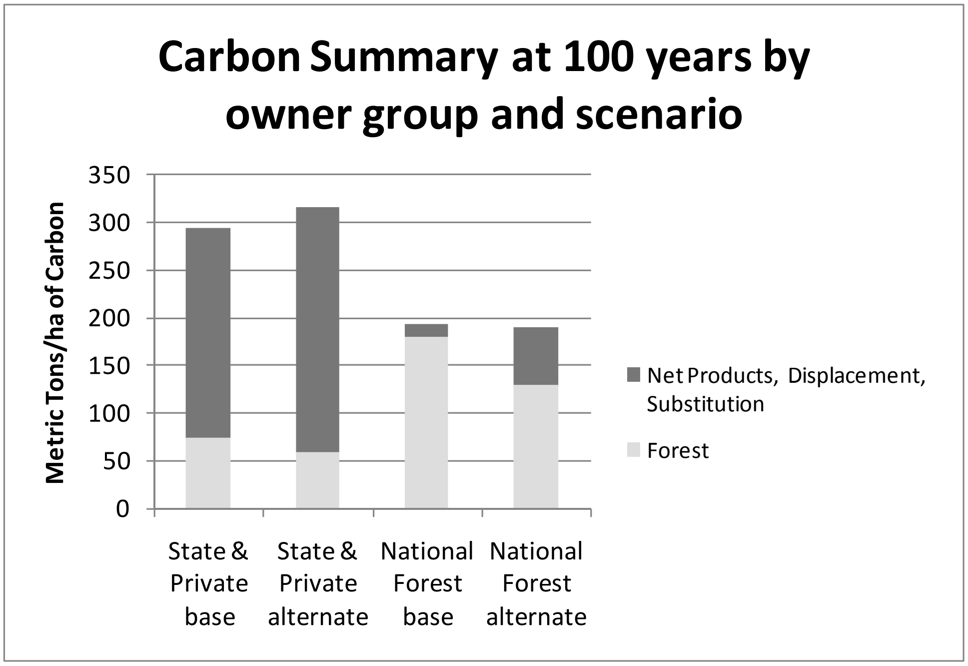

Figure 6: Carbon Sequestration and storage after 100 years by owner group and scenario

Table 2: Metric tons/hectare of carbon produced in the forest and in all carbon pools by decade and owner group

	Forest				**Forest, Products, Emissions, Displacement, Substitution**			
Year	**State & Private base**	**State & Private alternate**	**National Forest base**	**National Forest alternate**	**State & Private base**	**State & Private alternate**	**National Forest base**	**National Forest alternate**
2005	44	43	77	70	61	63	83	99
2015	47	43	91	75	83	85	99	111
2025	47	45	106	78	102	102	114	120
2035	51	48	121	84	121	124	129	126
2045	56	52	123	90	142	145	132	133
2055	59	54	135	101	173	178	144	145
2065	60	54	145	105	198	203	158	169
2075	60	50	155	110	230	241	167	172
2085	65	54	164	118	246	257	175	171
2095	69	58	173	124	275	288	184	183
2105	74	59	180	129	294	317	193	191
2115	78	60	187	133	318	342	202	204

Fire Impacts on Carbon Estimates

While no attempt is made to model the stochastic nature of fire, applying the average annual historic estimate of area burned over the entire simulation period and comparing the impact with the doubled rate expected with climate change provides a useful sensitivity range on impacts. This method of analysis identifies the limits to carbon accumulation associated with climatic controls on fire behavior without explicitly evaluating how increasing inventory leads to increasing fuel loads and higher fire risk.

Figure 7 shows the forest carbon impact from the assumption of no fires, the impact of applying the historic fire rate consistent with 12% refugia area not burning in 100 years, and the impact of a doubling of the fire rate under moderate climate scenarios. All of the increased forest carbon modeled under a no fire assumption is lost to wildfires using the historic fire rate in the simulation. Figure 7 also shows that the wildfire rates predicted under moderate climate change scenarios reduces forest carbon by over half the current storage in live trees.

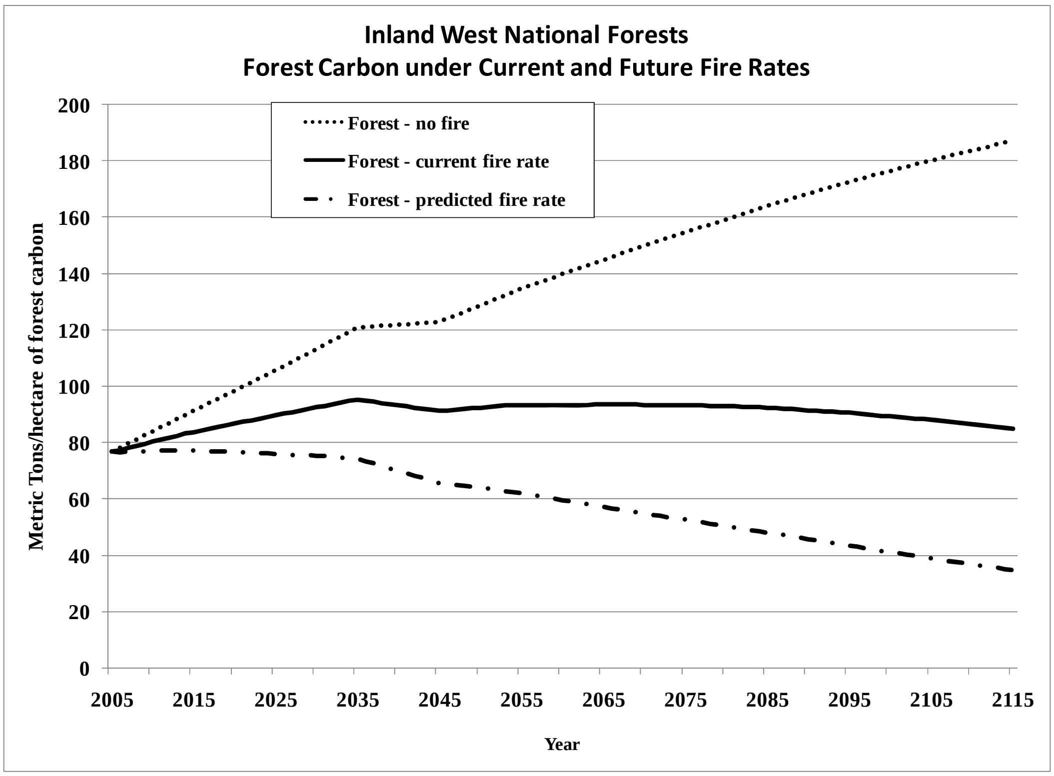

Figure 7: Forest Carbon – Inland West National Forests with current management and three fire rate assumptions

Discussion

Combining the historic landscape analysis of Camp et al. (1997) with the climate change predictions of McKenzie et al. (2004) suggests that increasing storage of forest carbon on unmanaged forest lands subject to these kinds of disturbance pressures is not probable given current and expected future climate conditions. It is probable that there will be a negative feedback on acres burned as fuel availability declines with increasing area burned, but uncertainties about the timing, extent, and impact of the feedback are unknown and probably large.

Under current management intensities there are few opportunities to store any of the new growth as carbon in products or displacement of fossil intensive products resulting in less carbon stored per ha from National Forest lands than is stored on actively managed state and private forest lands from 55 years forward in the simulation (Figure 1). This suggests that the thinning treatment simulations under the alternate case (Figure 5) provide a better strategy to both restore forest health and remove excess fuels and carbon into off-site carbon pools.

While climatic controls have been implicated as the dominant predictor of area burned, thinning treatments that reduce fire risk have a high potential to reduce carbon emissions both by reducing wildfire intensity and/or acreage and in sequestering carbon in the products produced from the material removed (Mason et al. 2006, Lippke et al. 2006). However thinning treatments need to be introduced rapidly to reduce fires significantly and the carbon accounting and methods to motivate such treatments are complex, involving both the type of treatment, the rate treatments are phased in, owner objectives, and the use of wood removed from the forest (Lippke et al. 2008). While the fire impacts modeled here are for National Forests where fuel loads are highest and therefore risks are most severe, there are some state and private lands with high fire risk, and even those that are not, may be at risk from contagion from adjacent forests with high fire risk. Whether this suggests thinning to lower densities is needed to provide greater resilience to climate change is not clear, but it does provide motivation to thin more stands quickly to reduce the impact of the increasing fire risk.

The thin from below strategy simulated for National Forest lands resulted in a very large volume of non-merchantable material. With the changing economics produced by higher carbon values, currently non-merchantable forest residuals could be collected as a source of green electricity or biofuel. There is 50 t/ha of residual material that must be disposed of under the base case and 80 t/ha for the alternate case. Recovering even a portion of these residuals would substantially improve the carbon profile of these restoration activities, while offsetting fossil fuel emissions. At the current time they are burned to reduce fire risk, or decay in situ, both of which release carbon back into the atmosphere. Thinning treatments that are not strictly limited to trees less than 12 inch in diameter or which remove greater amounts of material can increase the carbon pools outside of the forest. They are also likely to reduce the risk of fire (Mason et al. 2006) while increasing forest resilience and reducing climate change related stress, depending upon climate sensitivities and stand carrying capacity.

While normal management treatments have shown no substantial impact on soil carbon, severe wildfires have the potential to substantially change soil carbon. The simulations do not capture the impact of more severe wildfires, which can remove over 25% of the soil carbon (Bormann et al. 2008), and where post fire hydrophobic soils can result in massive erosion events (Helvey et al. 1985), both of which reduce soil carbon, forest productivity and subsequent carbon gains and may even prevent forest regeneration in the most severe cases (Cromack et al. 2000). As soils can contain up to half the carbon in the forest, it becomes increasingly apparent how important it is to reduce the extent of severe wildfires caused by excessive fuel loads.

The interaction between wildfire and permanent loss of, or change in, forest cover is also a concern in the Inland West. In the southwest, forest dieback events associated with climate change have already occurred (Allen and Breshears 1998) and more are predicted (Breshears et al. 2009). Models suggest that one or more tree species will be lost in parts of the Inland West in the coming decades with wildfire being the most likely mortality agent, though insect outbreaks may also play a role (Littell et al. 2009). Extreme weather events, wildfire, insect outbreaks, and poor seed crops interacting in a disturbance complex may permanently alter the forest structure. While the modeling approximates forest carbon neutrality under sustainable management treatments, there are outstanding questions as to whether productivity and carbon sequestration will continue at the same rates as seen today. Our results suggest that if we rely solely on the forest as a carbon sink, then the total sink will be less than it is today. If we rely on the forest as a carbon pump, by removing merchantable growth and turning it into long-lived products, then even if the inherent productivity declines with climate change, the forests will still remain a carbon sink, rather than a carbon source.

Conclusions

In the Inland West, where the forest land base is dominated by federal ownership and the forests are managed for a multitude of benefits, life cycle analysis suggests that the optimal solution for maximizing carbon gain, under both current and future climate conditions, is to manage forests to maximize long-lived wood products and to minimize the risk of severe wildfires. The carbon storage in buildings and the substitution benefits therein override the potential gains of attempting to leave high carbon stocks stored in the forest. This result is augmented by the fact that leaving the carbon in the forest increases the risk of wildfires and thus carbon emissions and eliminates the opportunity to use the material to displace fossil intensive products.

There is a great need to integrate and assess how treatments can be used to mitigate the impacts of increasing areal extent of wildfire caused by climate change. Here we show the likely outcomes if we continue business as usual under an altered fire regime. Sensitivity analysis that incorporates impacts on fire severity and associated mortality into a doubled fire rate scenario is needed to determine the best treatments and how many acres would need to be treated in order to maintain forests as carbon sinks. Regardless of treatments, we can expect that forests of the Inland West will store less carbon in the future under an altered fire regime. However they can be managed as a carbon pump to grow the material which can be harvested, and sequestered in lower risk conditions.

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