Impacts of Thinning Intensity and Implementation Schedules on Fire, Carbon Storage, and Economics

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Abstract

The Consortium for Research on Renewable Industrial Materials (CORRIM) released a Life Cycle Inventory and Assessment study on wood demonstrating that for the Pacific Northwest, while longer forest management rotations increase the carbon stored in the forest, the corresponding reduction in carbon stored in long-lived products and the displacement of fossil intensive products such as steel or concrete, results in an overall reduction in carbon as rotation ages are increased. This raises interesting questions for the overly dense stands in the Inland West that are threatened by fire, a disturbance event that is dependent upon treatment history and timing. Management treatments are shown to reduce the fire risk and store more carbon but the probability of fire and the timing of treatments must be considered in estimating total carbon storage. Prototype methods are developed to demonstrate a likely path for carbon stored by incorporating both the probability of fire and the useful life of the products produced. The probability of fire on high fire hazard stands would appear to be sufficient to justify thinning treatments while also contributing to carbon storage so long as a substantial portion of the product is allocated to long-lived uses such as housing construction.

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Introduction

There is high interest in forest management treatments that can reduce the frequency and intensity of the abnormally hot and devastating fires that have been experienced in the Inland West in recent years (WGA 2001, 2002). Natural resource management policies are also increasingly being considered in the context of climate change. Fires release carbon stored in forests to the atmosphere, while treatments remove and store carbon in the form of products and potentially reduce fire hazard. Recent developments in both forest fire simulation models and carbon life cycle analysis models are contributing to an improved understanding of the relationship between fuel reduction treatment effectiveness and fire intensity at the stand scale, as well as the consequences for carbon release and storage. This study developed a prototype methodology to evaluate alternative fuel reduction strategies relative to changes in fire hazard, carbon, and economic impacts at the large landscape scale.

Fire Simulation Modeling

The development of the Fire and Fuels Extension (FFE) model as a link to the Forest Vegetation Simulator (FVS) model provided a significant advancement in stand level fire simulation analysis (Beukema et al. 1997, Crookston 1990, Dixon 2003, Scott and Reinhardt 2001). FFE predicts fire hazard, behavior, and mortality within

a forest stand based on tree inventory and fuel and weather characteristics. In fire science terminology, this modeling system allows FFE to predict first-order fire effects and FVS to predict vegetation (and fuel) change through time. Many analysis modules have been developed based on FVS tree-lists, such as habitat suitability models, economics, and carbon such that many ecological attributes can be analyzed in conjunction with treatments to reduce fire hazard.

Mason et al. (2003) used these models to investigate the relative benefits of fuel reduction activities by simulating management treatments with a wide range of thinning intensities (including no action) on a large number of forest types in the Okanogan and Fremont National Forests. Results were analyzed for fire hazard reduction effectiveness, the cost of the treatment, and the effects on selected environmental metrics. Many non-market values and downstream avoided costs were identified that more than offset the potential costs of treatments. Increased carbon storage is one of those benefits that will likely become more important as efforts increase to reduce greenhouse gas emissions.

While Mason et al. (2003) evaluated the effectiveness of alternative treatment intensities, all of the treatments were simulated in the initial year without considering the length of time it would take to phase in and complete a treatment program. Wildfire was also evaluated as a treatment for impact comparison to mechanical treatments designed to reduce fuel loads and fire hazard. This allows the direct comparison of fire and thinning treatments, and when coupled with predicted rates of fire that are dependent upon fire risk and the timing of mechanical treatments provides simulations to evaluate the impact of a practical implementation schedule of treatments over time for a large scale landscape.

Models have been developed to simulate fires, including the fire behavior and growth simulator FARSITE and vegetation change models such as LANDSUM, SIMPPLLE , and VDDT (Chew 1995, ESSA 2005, Finney 2004, Keane et al. 1997). A limitation for FARSITE, especially at large scales, however, is the need for detailed and spatially explicit information. The vegetation change models require large amounts of user-defined data input, including vegetation change pathways, without a close relationship to supporting models such as FVS (Barrett 2001). For this study, FVS was used to project tree-lists which in turn were used to evaluate economics, habitat, and carbon accounting based on new research in carbon life cycle analysis and to provide inputs to FFE for a fire hazard analysis.

Carbon Life Cycle Analysis Modeling

The Consortium for Research on Renewable Industrial Materials (CORRIM) has recently released reports covering the full life cycle assessment of the environmental performance of using wood products in residential construction (Bowyer et al. 2004a, Lippke et al. 2004, Wood and Fiber Sci. 2005). Included in this research is accounting for four major carbon pools:

1. carbon in the forest;
2. carbon in products that leave the forest;
3. carbon associated with the use of forest biomass and product residuals as an energy source; and
4. the carbon offsets from the substitution that occurs when wood building materials displace products such as steel or concrete, which are fossil fuel intensive in their manufacture and subsequently contribute to the release of greenhouse gases such as CO_2.

An important finding in the CORRIM report is that forests that are periodically harvested, planted, and regrown to produce a continuing series of short- and long-lived products and energy feedstocks, sequester and offset more cumulative carbon than forests that are left unharvested. This finding is illustrated by the graphs that depict carbon accounting associated with a managed forest shown in **Figure 1** and an unmanaged forest in **Figure 2** (Lippke et al. 2004). **Figure 1** characterizes the time dynamic nature of carbon storage for a 45-year commercial rotation in Western Washington as a cumulative sequence of carbon in the forest, in products, and the impact of the product in substituting for non-wood products. **Figure 2** shows the accumulation over time of carbon for the same beginning forest inventory, but with no treatments, no disturbances such as wildfire, and no products and hence no substitution for fossil intensive products or fuels.

While the carbon in the forest in **Figure 1** is shown to cycle with each rotation around a steady-state trendline, the carbon in product pools net of energy used in harvesting, processing, and construction increases slowly over time. When the carbon emissions from the displacement of fossil fuels by wood residuals used for energy generation and the displacement of fossil fuel intensive building products (such as steel and concrete) are included, there is a substantial trend increase in total carbon that can be seen to surpass the cumulative carbon storage in forest biomass when there is no harvest activity – as shown in **Figure 2**.

The CORRIM analysis provides a method for tracking the carbon through all important carbon pools but does not consider forest disturbances such as fire. When considered in the context of Inland West forest conditions, the findings in the CORRIM report for the Northwest raise interesting questions about the impact on carbon emissions resulting from intense forest fires as a consequence of failure to remove excessive fuel loads. Fires reduce the opportunity to produce long-lived products while creating regeneration challenges that may result in a loss of forest

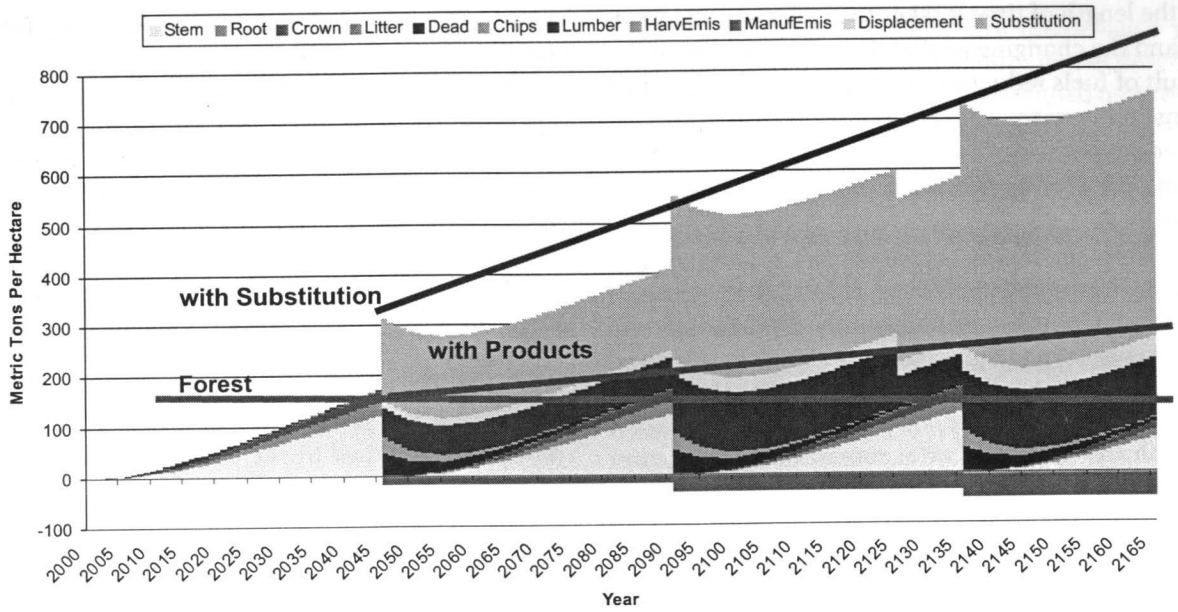

Figure 1. — *Carbon pools in a Pacific Northwest forest in products and energy displacement and fossil intensive substitutes (concrete frame vs. wood frame) with 45-year rotation.*

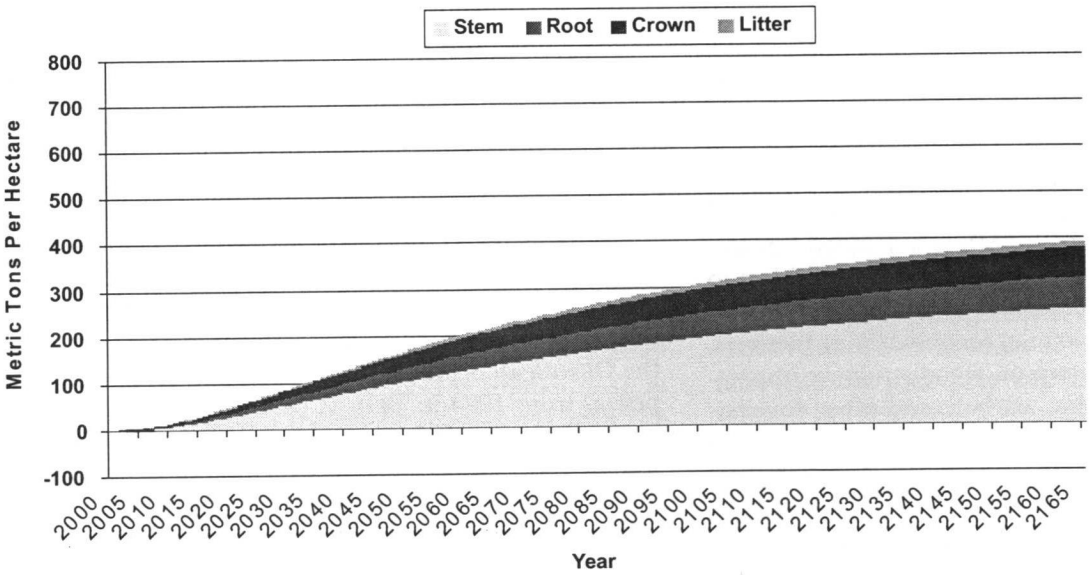

Figure 2. — *Carbon pools in a Pacific Northwest forest for stem, roots, crown, and litter with no harvest (no action) and no natural disturbance.*

productivity for extended periods of time. Forest fires also release large volumes of carbon into the atmosphere.

Study Objectives and Methods

This study addresses limitations in both the CORRIM analysis and the research by Mason et al. (2003) by incorporating fire disturbance into treatment regimes and carbon predictions (Bowyer et al. 2004b). First, a disturbance model to predict the frequency of fires was developed based upon the fire history of the selected National Forest. The disturbance model included the ability to calibrate the rate of new fires with the FVS-FFE predictions of fire hazard. After developing the disturbance model, the impacts of treatments are evaluated based on the treatments developed by Mason et al. (2003) for the Okanogan National Forest. Landscape management alternatives are developed to:

1. compare mechanical treatments intensities that reduce the fire hazard;
2. consider the consequences of immediate versus delayed treatments; and
3. include the probability of fire effects through time on forests that have a high and moderate hazard of crown fire as dependent upon growth and treatment history.

The resulting carbon storage, the risk of fire ignition and the magnitude of the forest fire hazard depends upon a combination of factors including the mechanical treat-

ments, the length of time it takes to implement the treatments, and the changing probability and intensity of fire as a result of fuels reduction treatments or fires and fuel additions from treatments and growth. The results are intended as a demonstration of a prototype methodology, with some simplifying assumptions used to enhance the tutorial value.

To develop landscape management alternatives, a non-spatial, forest stratum-based, area allocation model was developed to take advantage of the FFE and carbon life cycle analysis models recently developed for FVS and the Landscape Management System (LMS). Alternative treatment pathways were simulated for each forest strata, with tree list inventories representing vegetation conditions at each point in time. A fire disturbance (rate of burn) model was developed and incorporated into the area allocation model where the probability of fire in any given period is dependent upon the fire hazard classification of the forest vegetation which in turn depends upon treatments. LMS with FVS-FFE was used to simulate growth, treatments, fire, and produce per acre output metrics including acres burned, economics, carbon stored, and other ecological metrics.

Models and Simulation Data

The Landscape Management System (LMS) was used to simulate the impact of various treatment alternatives within the Okanogan National Forest in Washington State (McCarter et al. 1998). LMS is a detailed forestry software program that manages tree list data subject to harvest and growth simulations over time and is equipped with analysis modules for quantifying biomass, log quality and product outputs, stand structure impacting fire hazard and habitat, carbon, and other environmental and economic metrics. LMS has been designed to use any of a variety of growth models including the Forest Vegetation Simulator (FVS) created by the USDA Forest Service. FVS is an individual-tree, distance-independent growth and yield model (Crookston 1990, Dixon 2003). FVS can be used to simulate silviculture treatments along with growth and yield for most major forest tree species, forest types, and stand conditions. Variants of FVS provide growth and yield models for specific geographic areas of the United States. For this investigation, the East Cascades Variant of FVS was selected for use with Okanogan National Forest forest inventory data. The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) links existing FVS models, that represent fire and fire-effects, with newly developed fuels dynamics and crowning submodels (Beukema et al. 1997, Scott and Reinhardt 2001). The Fire and Fuels Extension (FFE) has been developed to assess hazard, behavior, and impact of fire in forest ecosystems (Reinhardt and Crookston 2003). FFE can produce reports of changes in various indices of potential fire severity as a result of alterations to stand characteristics resulting from simulated management alternatives.

Forest inventory data for the Okanogan National Forest were assembled from the Continuous Vegetation Survey (CVS). All plots were analyzed for stand structure characteristics and relative fire hazard (Hardy 2005). A high, moderate, or low fire hazard classification was assigned for each CVS plot in the simulation dataset based on the Severe Crowning Index assessment from the Potential Fire Report produced by FFE. The Crowning Index indicates the estimated wind speed in miles per hour (mph) at 20 ft off of the ground that would initiate an active crown fire assuming ignition of surface fuels. Assumptions required by the model include a temperature of 70°F and 'very dry' moisture conditions (Crookston et al. 2002). If the crowning index was ≤ 25 mph, then the plot was considered to be in the high fire hazard category. Moderate hazard stands were those with a Severe Crowning Index > 25 mph, but ≤ 50 mph. Low fire hazard stands were those with a crowning index > 50 mph. While relative fire hazard is actually a continuous function rather than discrete classes, there are tutorial benefits of transparency in effects when observing the transitions from one hazard class to another.

The Okanogan National Forest includes 216,403 acres of high fire hazard as evaluated on 117 inventory plots, 369,920 acres of moderate fire hazard on 200 plots, and 177,562 acres of low fire hazard on 96 plots. To simplify the analysis for a prototype demonstration of the methodology, one plot from each fire hazard classification group with attributes closest to the classification average was selected to represent the associated acres. Data for the Okanogan National Forest was collected during the period from 1994 to 1996. A base year of 1995 was selected as the start point. The 1995 CVS inventory data was "grown" forward within FVS for one growth period of 5 years to 2000 to initiate the treatment simulations.

Treatments

A range of mechanical treatment intensities were selected that have been developed in previous studies to provide an opportunity for broadest utility and research continuity (Mason et al. 2003, Fiedler et al. 2001). Treatments evaluated were:

- 12&Over: Removing trees 12 in. in diameter at breast height (DBH) and larger (12&Over), represents a selective harvest of the largest and most valuable trees. This treatment demonstrates a high short-term revenue yield that maximizes production of long-lived products. This treatment is reminiscent of past practices sometimes referred to as high grading.
- 9&Under: Removing trees 9 in. DBH and lower (9&Under) demonstrates a light touch attempt at lowering the fire intensity hazard while retaining

as much large tree biomass in the forest as possible. With this treatment little merchantable material is removed. This treatment was proposed for broad application on Inland West National Forests by Babbitt and Glickman (2000).

- BA45: Thinning from below to a target of 45 ft^2 basal area per acre (BA45) represents an opportunity to generate revenue while leaving the largest trees, reducing the ladder fuels that are known to increase the fire hazard, and returning the forest to more open pre-settlement conditions. For reference, 45 ft^2 of basal area per acre is approximately equivalent to 57 trees per acre that are 12 in. DBH.

Treatment Implementation Schedules

To evaluate the effect of timing, a set of simulations was developed for the 12&Over, 9&Under, and BA45 treatments. The expanded simulation set included management pathways with the treatments allocated equally to each 5-year interval from 2000 to 2020 for a 25-year phase-in of the treatments. This set resulted in three treatments intensities with five treatment schedules (15 simulations in total).

Next, a set of simulations accounting for the timing of fire was developed for each treatment set. For each management pathway, a set of potential disturbance pathways was developed with the fire event occurring in each 5-year modeling interval from 2000 to 2050. If the inventory was classified as low fire hazard in the period when a fire was to occur, however, the fire event did not occur. The total number of potential treatment simulations developed was: three treatments intensities with five treatment schedules with 11 fire events (165 simulations). In addition, 11 no action treatment simulations with fire events were modeled.

To reduce simulation time, only two fires events were simulated: the high hazard group and moderate hazard group representative inventories in 2000. Post-fire inventories were then simulated with no action until 2050. When fire events occurred in a pathway, post fire values were based on one of these two simulations rather than updating the inventory each period. While this is a compromise in fire predictions for a specific year, because fire hazard classification was still based on actual inventories that change relatively slowly, this post-fire simplification was considered acceptable for demonstration of landscape level trends.

The full set of simulations completed for each representative inventory determined the 176 potential management and fire disturbance pathways for the high, moderate, and low fire hazard groups. An area allocation model was then used to develop management scenarios for the Okanogan National Forest. The percentage of group acres following a particular treatment pathway was controlled directly; however, the percentage of those acres following a particular fire disturbance pathway was controlled by a fire probability model described below. Acres that burned before a scheduled treatment were not mechanically treated.

Fire Probability Model

A deterministic fire disturbance model was created based on the portion of landscape susceptible to burn defined by the same fire hazard classification used to stratify the initial Okanogan National Forest inventory. A user-defined percentage of area in each class was burned for each time period, resulting in assignment of acres from the original treatment pathway to the appropriate treatment with disturbance pathway. Treatment pathways reduced the frequency of fires by moving stands out of higher hazard classes. The model allows separate burn rates to be set each period for each hazard classification.

The model was calibrated for cumulative acres burned over the entire simulation time period and for acres burned during each 5-year simulation cycle based upon investigations of refugia thought to have resulted from pre-settlement fire behavior. Camp et al. (1996), in an investigation of historic fire behavior in the Wenatchee National Forest, found evidence to suggest that, prior to European settlement, most of the forest burned regularly in short fire return intervals with the exception of scattered pockets of refugia primarily located in moist areas such as north facing slopes and riparian zones. Study results estimated that unburned pre-settlement refugia accounted for approximately 12 percent of the study area and less than 20 percent of the broader landscape. Olson (2000) found that in areas of Oregon's Blue Mountains and Cascades that there was little if any refugia that remained fire free prior to European settlement including riparian areas. While predicting the timing and intensity of fire ignitions is problematic, Camp and others suggested that present risks and hazards of ignition and crown fire in overstocked forests are reasonably much higher than that of pre-settlement conditions. Subsequently, in many forests that have grown over the last century into homogenous densely stocked landscapes with high hazard fuel loads and no fuel breaks, intense crown fires will likely burn through entire areas, some of which may have previously been refugia. For this study, however, a target of 18 percent fire-free refugia was chosen to be retained across the high fire risk landscape as a credibly conservative target for areas that might remain unburned during a 50-year simulation period. Refugia was defined for those acres classified as high hazard initially. The remaining 82 percent was "burned" based on an equal probability distribution of fires in the high fire risk forest acres during each 5-year simulation cycle.

To demonstrate a relationship between hazard severity and fire frequency, the moderate hazard group was assumed to be approximately half as likely to burn as the

high hazard group, and low hazard stands would be unlikely to burn (0% probability) as long as they remained in that hazard class. Through trial and error, a 14 percent periodic burn probability for the high hazard group reduced the refugia to about 18 percent by 2050. For the entire Okanogan National Forest, since the burn rate for the moderate hazard was only half that of the high group and the low group did not burn, the number of unburned acres by 2050 was still much higher than the 18 percent refugia target. This is illustrated in **Figure 3**. These periodic burn probabilities were applied to each landscape scenario. To simplify this demonstration, the potential impacts of forest fires in previously burned forests were ignored by assuming that, once burned, an area does not reburn before the end of the investigation period, even in cases where simulated hazard class returns to high and moderate conditions.

Landscape Scenarios

In addition to the immediate treatment schedule including fire, an additional set of treatment scenarios were phased in over 25 years to demonstrate the comparative impacts of a designed thinning treatment schedule. In the first landscape simulation set, all high and moderate fire hazard acres were treated with 12&Over, 9&Under, and BA45, and all treatments occurred in 2000. These landscape scenarios were titled '12&Over Immediate', '9&Under Immediate', and 'BA45 Immediate'. A 'No Action' treatment with fire disturbance events was also included. In the second set, the 25-year phase-in of treatments was demonstrated with 20 percent of the high and moderate hazard acres available in each 5-year interval treated during the five modeling cycles from 2000 to 2020. These landscape scenarios were titled '12&Over 25 Yr Phase-In', '9&Under 25 Yr Phase-In', and 'BA45 25 Yr Phase-In'. For all of the treatment scenarios, only acres in the high or moderate hazard group in 2000 were considered for mechanical treatment during the 25-year phase-in; however, all acres were subject to burning with the burn rate dependent upon hazard class. For all seven landscape scenarios, all of the acres (treated, untreated, burned, unburned) were simulated in 5-year growth cycles to the end of the investigation period at 2050.

Assessment of Fire Hazard, Carbon, and Economics

Fire hazard, carbon, and economic management outcomes were analyzed at the end of each 5-year model interval for each landscape scenario. To evaluate fire hazard reduction effectiveness, the number of acres burned, low hazard acres, and unburned acres were calculated. Results were based on the fire hazard classification evaluation developed from the Fire & Fuels Extension (FFE) to FVS.

A life cycle assessment of environmental burdens developed by CORRIM serves as an accounting system for the carbon consequences of forest management alternatives (Manriquez 2002, Perez-Garcia et al. 2005). Estimates of changes in the amount of carbon stored over time in the standing forest are calculated using biomass to carbon conversion factors specified by species for tree bole, bark, foliage, limbs, and roots. Any material harvested is exported to product manufacturing or left to decompose, a carbon loss. Estimates of carbon stored in each type of harvested wood products are also calculated with short-lived products such as chips for paper subject to fairly rapid decomposition. Estimates of carbon emitted to the atmosphere from harvesting and manufacturing operations are considered as reductions to carbon stored in wood products. Estimated as well is the amount of carbon not emitted by the reduction in fossil fuel energy generation by wood used in a wood boiler for heat and energy, a partial offset to the total processing energy used in manufacturing, and the substitution of wood for concrete frame as the prevailing non-wood construction material. The model is implemented in Microsoft Excel and works in tandem with LMS, allowing a comprehensive estimate of forest carbon storage, substitution, and

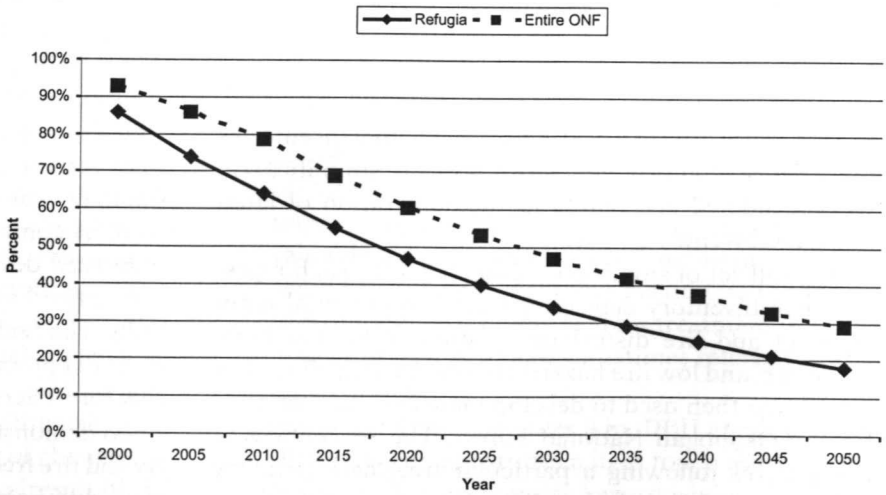

Figure 3. — *Unburned Okanogan National Forest and high fire hazard refugia through time with no thinning treatments.*

displacement over time for different management alternatives. This carbon assessment process is based on studies of wood biomass carbon content, decomposition, product utilization harvesting and manufacturing, purchased energy emissions, biofuel use, and construction alternatives (Birdsay 1992, Bowyer et al. 2004, Franklin Associates 1998, Gholz et al. 1979, Harmon 1992). Changes in forest biomass from growth (simulated with FVS) and decomposition are simulated and converted to stored carbon pool estimates. Carbon amounts are moved from the forest to the products pool following a silvicultural operation, simulated in LMS. The model calculates log utilization to determine amounts of short-term and long-term products. These products are either decomposed through time or used for biofuel (short-term) or product substitution (long-term). Emissions from harvesting and manufacturing are determined from the types of silvicultural treatments performed and the amount of harvest volume removed and processed.

Three broad categories of carbon are used to characterize impacts: forest, products, and substitution. Products carbon is calculated as net of all carbon releases associated with harvesting and processing activities. The biofuel resource generated from product manufacturing residuals such as, bark, sawdust, planer shavings, etc. is modeled as an energy resource offsetting some of the carbon emissions generated from the fossil energy sources otherwise used in manufacturing. The biomass for bioenergy reduces the carbon in the forest but offsets much of the fossil fuel energy and related carbon emissions that would otherwise need to be purchased for harvesting and product manufacture. The long-lived product volumes such as lumber and panels displace non-wood products such as steel and concrete which are more energy intensive in manufacture. For this study, total carbon (forest, products, and substitution) are presented with more detail provided in Lippke et al. (2006).

An economic analysis was provided for treatment costs and firefighting costs. An average net return or cost per acre was calculated for each thinning treatment based upon harvest economic results generated in a previous study of the Okanogan National Forest by Mason et al. (2003). These values are provided in **Table 1**. Total present value of revenues and costs associated with fuels reduction treatments for each treatment intensity expanded to reflect landscape outcomes was calculated by multiplying the per acre values for corresponding treatments by the number of acres treated in each time interval. All revenues and costs were then discounted back to the start year to generate a net present value (NPV) estimate for each series of treatments (**Table 2**).

Averages of historic firefighting costs are used to estimate the future benefit of lowering fire hazard through fuel reduction activities. While precise assessments are impossible, approximations of the value trade-offs associated with investments today to avoid future hazards are useful. Plots thinned to remove fuel loads have been shown to be unlikely to experience crown fires (Omni and Martinson 2002). Accounting for the value of that reduced hazard exposure must take into consideration both the consequences of not thinning and the reduction in cost by thinning adjusted for the time value of money. The savings of future firefighting costs must be discounted to an expected present value based upon either a reasonable estimated time to fire or based upon a distributed fire event probability such as provided by the above simulation.

Table 1. — *Net returns from harvesting treatments with high, low, and average logging costs.*

Treatment	High logging costs	Low logging costs	Mean net return
12&Over	$1,025	$1,953	$1,489
9&Under	$ (345)	$ (287)	$ (316)
BA45	$ (169)	$ 291	$ 61

For this investigation, firefighting costs were estimated to be $1000 per acre; reflecting the approximate average firefighting costs for the Okanogan National Forest for the last decade. It is worth noting that the comparable cost for non-federal firefighting costs in Washington (WADNR 2004) is over $2000 per acre largely due to the greater number of large fires on federal acres with less intensive suppression activities. The landscape cost was determined by multiplying the number of acres burned each period by the firefighting cost. A 5 percent discount rate was used to convert all future anticipated firefighting cost liability exposures to present value dollars (**Table 2**).

Discussion of Results

Post treatment results are tabulated in **Table 2** for acres burned and unburned, acres categorized by hazard class, carbon, and economics. Total carbon values are provided in million metric tons for the Okanogan National Forest. Economic results are provided for the net present value of treatments for each landscape scenario (Harvest Value NPV), the net present value of firefighting costs for each landscape scenario (Firefighting NPV), and total net present value (Harvest Value NPV + Firefighting NPV). All NPV values are provided in million dollars using a 5 percent discount rate. Results are provided for both an "Immediate" treatment and a "25 Yr Phase-In" and segmented between the first half of the simulation and last half to demonstrate the sensitivity to regrowth after initial treatments.

Model Critique

The simple fire disturbance model assumes that fire frequency is based on the abundance of high and moder-

Table 2. — *Results for three analysis periods: acres burned, low hazard acres, acres unburned, forest carbon, total carbon, and economics.*

	NA	12&Over Immediate	9&Under Immediate	BA45 Immediate	12&Over 25-yr Phase-in	9&Under 25-yr Phase-in	BA45 25-yr Phase-in
Fire Risk Reduction (acres)							
Acres burned/period							
Mean: 2000–2020	60,375	63,334	47,546	18,341	60,967	51,198	32,033
Mean: 2025–2050	40,324	39,708	35,136	48,247	40,201	34,006	35,562
Mean: all years	49,438	50,447	40,777	34,653	49,640	41,820	33,958
High hazard acres							
Mean: 2000–2020	234,496	345,845	112,358	0	268,573	134,978	76,260
Mean: 2025–2050	190,680	176,979	67,964	104,120	187,940	64,133	37,005
Mean: all years	210,596	253,736	88,143	56,793	224,591	96,335	54,848
Low hazard acres							
Mean: 2000–2020	234,896	320,089	270,081	525,729	264,639	240,802	421,769
Mean: 2025–2050	198,010	197,387	165,285	177,105	198,757	161,324	184,928
Mean: all years	214,776	253,161	212,920	335,570	228,703	197,451	292,583
Unburned acres							
Mean: 2000–2020	590,415	584,496	635,700	735,057	590,267	613,191	659,736
Mean: 2025–2050	305,613	292,049	393,953	509,605	302,900	379,332	485,188
Mean: all years	435,068	424,979	503,838	612,083	433,521	485,632	564,528
Carbon Impact (million metric tons)							
Forest carbon							
Mean: 2000–2020	25.9	18.2	23.2	17.9	21.5	24.6	21.5
Mean: 2025–2050	24.0	21.1	24.8	22.7	20.3	24.3	20.7
Mean: all years	24.9	19.8	24.1	20.5	20.9	24.4	21.1
Total carbon							
Mean: 2000–2020	25.9	35.7	27.8	30.7	31.4	27.0	29.5
Mean: 2025–2050	24.0	37.5	29.0	34.7	35.0	27.7	33.0
Mean: all years	24.9	36.7	28.5	32.9	33.4	27.4	31.4
Economics (million $)							
Harvest value							
NPV: all years	0	$ 873	$ (185)	$ 36	$ 457	$ (100)	$ 20
Firefighting costs							
NPV: all years	$ (237)	$ (241)	$ (181)	$ (90)	$ (237)	$ (202)	$ (147)
Total value							
NPV: all years	$ (237)	$ 632	$ (366)	$ (54)	$ 220	$ (302)	$ (127)

ate hazard acres. At the landscape scale, this parallels the recognized historical trend in interior western ecosystems: as the number of high risk acres has increased, wildfire magnitude and intensity have also increased. At more site-specific scales, this assumption oversimplifies the complex nature of forest fire events. Directing treatments at certain terrain and fire breaks may have a greater impact in reducing fire hazard than the simulations suggest. Results are, therefore, most appropriate to compare relative differences between management alternatives at the landscape scale.

For simplification purposes, fire events were limited by the number of times an acre could burn. Both the characteristics of a second burn and the probability of such a burn are different than a first burn in many years. Predicting the rate that ladder fuels are restored through regrowth is difficult. Because reburns are realistic within the analysis period (55 years), the assumption of no reburns most probably biases the burn rate down for later time periods. Since growth rates are relatively slow in interior forests; reburned acres would likely contain lower amounts of carbon, so the reburn assumption should have relatively little impact on carbon results within the analysis period. To further isolate this assumption, results were provided for three time periods: 2000–2020, 2025–2050, and the entire analysis period.

Fire Hazard Reduction

The effectiveness of treatments in reducing the number of high hazard acres and raising the number of low hazard acres (reducing fire risk) compared to No Action is shown in **Figures 4 and 5**. The BA45 treatment elimi-

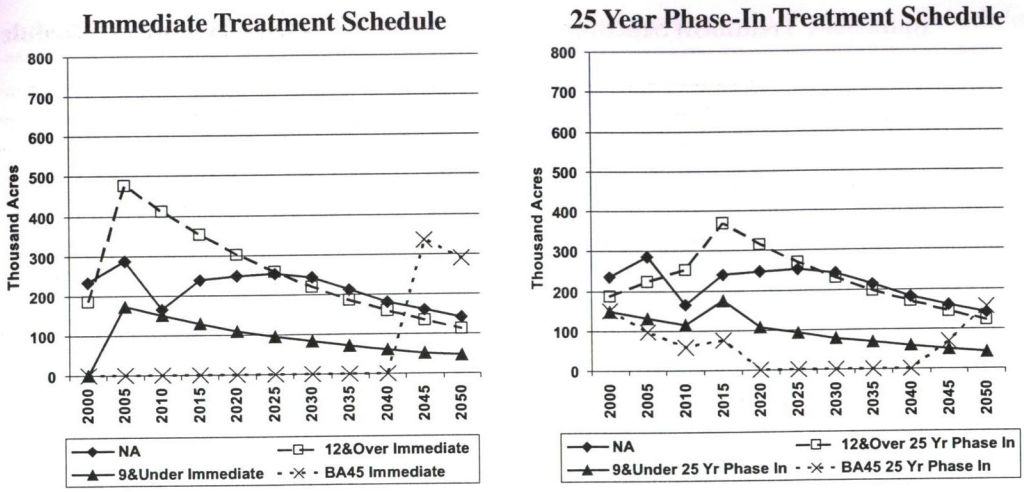

Figure 4. — *High hazard acres in each 5-year period by landscape scenario.*

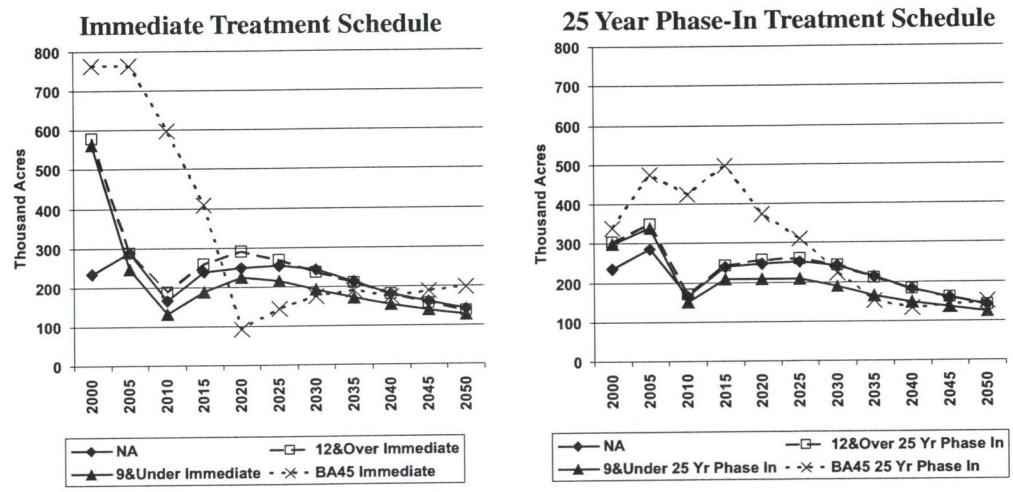

Figure 5. — *Low hazard acres in each 5-year period by landscape scenario.*

nates high hazard acres for almost 45 years but the transfer of treated stands to low hazard acres declines quickly, first from continued stand growth in the initial low hazard acres moving them up to moderate hazard and then from regrowth after treatment. After 20 years, the hazard begins to return unless a second round of mechanical treatments or controlled burns are implemented. Neither the 9&Under or the 12&Over treatment reduce the ladder fuels enough to reduce the hazardous acres for more than a few years. While the 9&Under treatment does reduce some acres from high to moderate and some from moderate to low this transition lasts for only a few years as the initial low hazard acres move quickly into the moderate class, whereas the heavier BA45 treatment takes longer for this transition. Similarly the 12&Over treatment retains most ladder fuels and the transition to lower exposure is minimal even though the character of fire would be changed. The No Action alternative results in a steady rate of fires and new burned acres maintaining 25 to 30 percent of the acres in the low hazard category much like the initial condition, but with a high fire hazard for a large portion of the remaining acres.

With the more feasible 25 Yr Phase-In period the share of acres in the low hazard class for the BA45 treatment increases by about 80 percent over the alternatives but restoration of hazardous undergrowth reduces the benefit after about 25 years.

If all of the at risk acres could be treated with BA 45 immediately, **Figure 6** shows that the acres burned each period would fall to low levels for 20 years but without continued treatments be no better than the other alternatives after 20 years. But, for the 25 Yr Phase-In, the rate of burn is cut almost in half from 60,000 acres per year to 32,000 per year. The increase in acres burned after 15 years under the No Action alternative is a response to the decline in the low hazard acres as growth moves stands to a higher hazard class.

As a caveat, fire hazard trends would likely be more gradual and slower to transition. Using a continuous fire hazard function rather than discrete hazard categories and greater resolution in grouping would capture more variation and smooth out the transitions. Some initially low hazard acres may also be at the forest-range interface. These marginal forests might not be expected to ever grow into the moderate hazard class due to very lim-

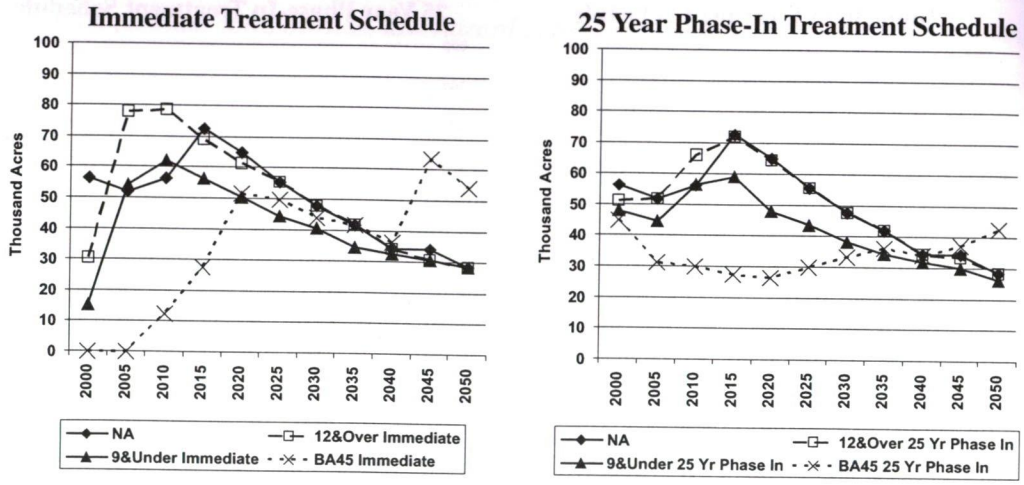

Figure 6. — *Acres burned in each 5-year period by landscape scenario.*

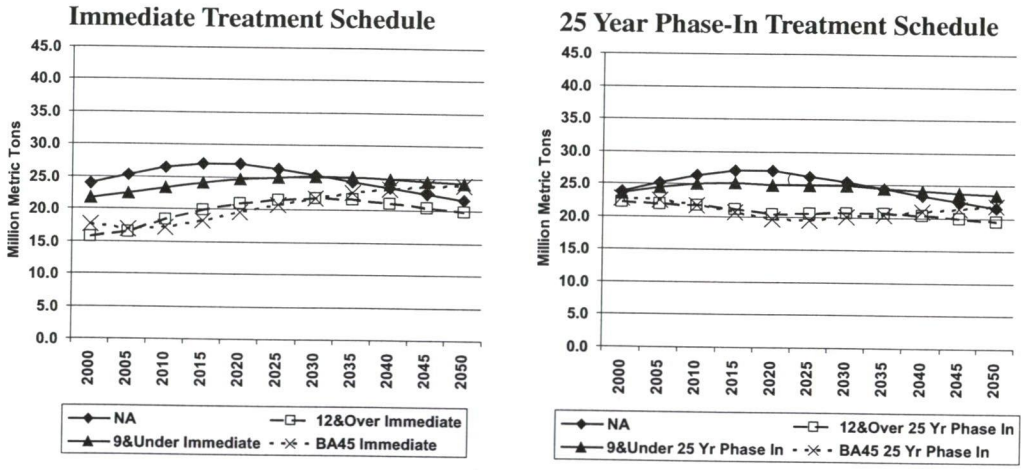

Figure 7. — *Forest carbon over time by landscape scenario.*

ited growing space and grazing. But, forests that have unprecedented fuel loads, more homogenous fuel load distributions than patchy pre-European forests, and are decades outside of historic fire return cycles are likely to burn larger acreages with intense fires sooner rather than later (Hessburg et al. 2005).

During later periods, the number of acres that burn steadily decline as many of the high and moderate hazard acres have experienced fire simulations by this time and conservative assumptions on not considering reburns in the simulation interval reduces the number of acres eligible for ignition. Reburns could occur within the 55 year analysis period and could be expected given the drop in low hazard acres shown in **Figure 5**.

If forests are thinned heavily from below to remove ladder fuels, and understory regrowth is periodically burned or otherwise removed, stands are more likely to grow into more sustainable savanna conditions. These stands would be characterized by sparse densities of large overstory conifers with high crown bulk density, and be more resistant to fire (Everett 2005).

Carbon Impacts

The carbon estimates for the No Action simulation **Figure 7** show increasing carbon in the forest until 2015 and coincident with increased fires, decreasing carbon during the latter time periods (2015–2050). Nearly 5 million metric tons of carbon are released into the atmosphere during the analysis period due to forest fire events. The influence of high mortality disturbance events such as forest fires results in very different carbon estimates for No Action scenarios when compared to the no action/no disturbance west side example shown earlier (**Fig. 2**).

All treatment scenarios remove carbon from the forest, resulting in lower mean carbon in the forest during the early periods (2000–2020). The BA45 and 9&Under scenarios, however, resulted in more carbon in the forest by 2050. Differences in forest carbon between scenarios can primarily be attributed to fire hazard reduction effectiveness which decreases the number of fire events (burned acres) that release carbon into the atmosphere.

Figure 8 shows that all of the treatment scenarios result in more total carbon than No Action when a more

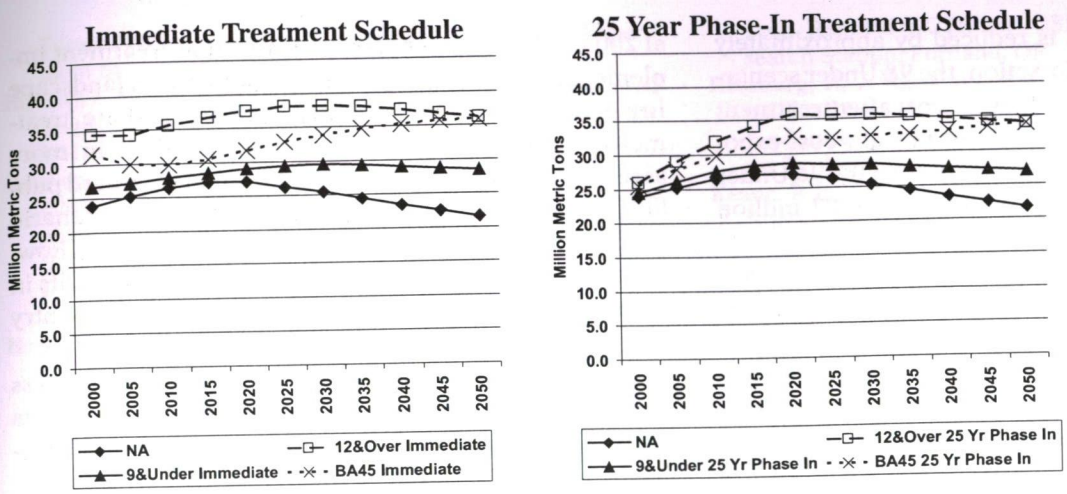

Figure 8. — *Total carbon (forest, products, and substitution) over time by landscape scenario.*

complete systems perspective is taken that includes carbon in products and avoided emissions. The No Action scenario results in higher burn rates effectively capping the amount of carbon stored in the forest with the carbon increasing emissions in contrast to treatments that capture more of that carbon in longer lived product storage such as housing. While the 12&Over treatment moves larger volumes into long-lived products quickly, since it does not reduce fires effectively the BA 45 treatment in time catches up. BA45 both reduces fire hazard and generates wood products that also substitute for fossil intensive products. Over the total period, BA45 stores about 6.5 million metric tons more than No Action compared to 8.5 more for 12&Over. The benefit of reduced fires builds up over time with BA45 producing 12 million metric tons more carbon than No Action by the end of the period. The CORRIM model accounting highlights the significance of life cycle analysis for a better understanding of stored carbon and avoided emissions from short- and long-lived products and fossil fuel offsets for assessment of alternative treatment trade-offs. Results will, of course, vary with the degree to which biofuels are used to displace fossil fuels as well as more or less substitution of wood for steel or concrete in building alternatives. But, coupling CORRIM research with studies on fire hazard reduction demonstrates the complexities inherent in development of successful strategies for carbon emissions reductions in the Inland West.

When comparing treatments to No Action in percentage terms the increase in the mean total carbon storage is substantial (26% during the total analysis period, 38% during the later period between 2025 and 2050, and more than 50% by the end of the 50-year period). **Figure 7** demonstrates that the high carbon in forest biomass associated with the No Action alternative cannot continue to increase. Over time the high and moderate hazard classes (highest biomass and carbon stores) experience forest fires with subsequent carbon release

Not unlike fire hazard reduction effectiveness, the carbon results for the 25 Yr Phase-In scenarios demonstrate reduced impacts from delaying treatments. BA45 Phase-In is 5 percent below BA Immediate over the total period, with the difference somewhat less at the end of the period. When the carbon releases associated with fire events are considered, it is apparent that delaying implementation of fuels reduction activities can result in a significant compromise to overall treatment effectiveness.

Economic Tradeoffs

A simple economic analysis is provided to demonstrate tradeoffs between scenarios. Due to estimated recurring firefighting cost liabilities, the simulations show that failure to reduce fuel loads (No Action) results in a public cost exposure for fire suppression activities through the simulation period of approximately $237 million (NPV **Table 2**). If weather events contribute to forest fires occurring sooner, this estimated cost of suppression would logically increase.

Harvest returns and fuels treatment costs, as mentioned above, indicate that treatment alternatives could result in net revenue or cost depending upon the amount and value of merchantable logs removed in the treatment simulation. The composite economic analyses for the treatment scenarios presented here examined the interaction between reducing firefighting costs by lowering the fire hazard and incurring additional treatment costs or generating revenue from log and slash removals. The 12&Over scenarios (Immediate and 25 Yr Phase-In) resulted in the only total value positive returns, due to the high value of wood removed. The 12&Over treatments, however, were least successful at fire hazard reduction and resulted in the most acres burned. Log revenues removed early in the period were of sufficient magnitude to absorb high firefighting costs.

The 9&Under scenarios (Immediate and 25 Yr Phase-In) result in negative treatment values and provide only marginal fire hazard reduction. While the net present

value of firefighting costs is reduced by approximately $56 million compared to No Action, the 9&Under scenarios produce the largest overall public cost after treatment expenditures are included. Total net present cost exposure for the Okanogan National Forest with the 9&Under Immediate treatment is $366 million and $302 million for 9&Under 25 Yr Phase-In.

The BA45 scenarios (Immediate and 25 Yr Phase-In) produce marginal but positive average thinning treatment returns of $61 per acre. Therefore, differences from No Action are almost entirely caused by the reduced fire hazard and subsequent firefighting costs. The BA45 scenarios resulted in significant reduction of net present public cost exposure as compared to No Action: nearly $183 million less for BA45 Immediate and $110 million less for BA45 25 Yr Phase-In. Note that while the BA45 scenarios appear most successful in achieving the range of management objectives considered, the BA45 scenarios still result in costs greater than revenue. Tthe difference between the magnitude of the positive return generated by the 12&Over Immediate (in spite of higher fire-fighting expenses) and the BA45 Immediate, however, may indicate that a slight modification in this treatment prescription to increase merchantable timber removals could provide a cost neutral hazard reduction option while still maximizing carbon storage and restoring large-diameter savannah-like forest conditions. As with other management objectives, the cost of delaying treatments can be quantified, with total savings reduced by nearly 40 percent for BA45 25 Yr Phase-In as compared to BA45 Immediate.

It was noted earlier that fire suppression costs on non-federal acres are roughly twice as high as on federal acres increasing the return for treatments. If in addition to firefighting costs, other avoided costs such as fatalities, facility losses, and regeneration costs are included, the treatment schedule with the least number of acres burned will provide the most favorable economic result (Mason et al. 2003). That is, the net cost of BA45 would be reduced while that of 12&Over would increase. Average values are only appropriate for relative comparisons of landscape trends and treatment performance. A more comprehensive landscape-level hazard reduction would logically include a mix of customized treatment intensities sensitive to actual inventory conditions, public values at risk and local concerns.

Conclusions

Previous research has demonstrated that treatment thinning intensity is an important factor in successful stand fire hazard reduction. On a national forest, several thinning intensities could be successful depending on site-specific forest inventory conditions, with heavier thinnings from below (BA45) typically being more successful in most forest conditions (Fiedler 2001, Mason et al 2003). This research demonstrated that treatment implementation timing is an important factor in landscape fire hazard reduction. Compared to immediate treatments, delayed treatment schedules resulted in more acres burned, decreased total carbon, and increased public exposure to firefighting costs. The No Action scenario produced the worst results. Benefits from thinning, however, may be relatively short-lived as re-growth results in increased hazard within about 25 years. Periodic re-entry for fuels removal is required to keep the fire hazard low.

The complex accounting required to accurately assess carbon strategies for high fire hazard Inland West forests was also demonstrated. The No Action scenario illustrated that the disturbance-free Pacific Northwest forest carbon projection (**Fig. 2**) while realistic for wetter coastal forests does not accurately reflect Inland West carbon storage and emissions where frequent and intense fire disturbances are expected. In the long-term, the most carbon in the forest will likely be stored by successfully reducing fire hazard and the number of acres burned. Simulations also demonstrate that while fire reduction treatments remove carbon from the forests, much of the carbon is then stored in long-lived products. When total carbon accounting is considered, the No Action scenario results in significantly more carbon emissions to the atmosphere than all other landscape scenarios. From a carbon storage perspective the most attractive scenario includes production of long-lived products from as much of the volume as practical, using the remaining residuals as a biofuel and reducing fire risk.

The ability to use FVS and FFE to predict forest vegetation growth, treatment impacts, and fire impacts, and any of the tree list analyses developed for LMS to predict other results such as carbon provides many advantages. Basing landscape results on FVS and LMS creates consistency between multiple modeling and planning scales, as FVS and LMS are designed to support site-specific, individual stand management decisions for operational or planning support.

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