

Carbon Benefits from Fuel Treatments

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Abstract—Landscape simulation modeling is used to examine whether fuel treatments result in a carbon offset from avoided wildfire emissions. The study landscape was a 169,200-acre watershed located in south-central Oregon. Burn probability modeling was employed under extreme weather and fuel moisture conditions. Expected carbon stocks post-treatment, post-wildfire were calculated for all stands on the treated landscape; post-wildfire on the untreated landscape. Results show a negative carbon offset initially—the known reduction of carbon stocks from treatment is greater than expected carbon benefit from reduced wildfire emissions. Treatment may break even as a carbon offset after 9 years.

Introduction

Many of the forests in the western United States (U.S.) are significantly altered as a result of decades of continuous fire suppression activity. The absence of wildfire in many forest types that historically have had frequent fire return intervals results in increased density of overstory trees and understory vegetation. Competition for limited moisture and nutrients further reduces tree growth and vigor. Add drought, insects or disease and the result is a perfect storm for uncharacteristically severe wildfire events—overstocked stands containing dead trees, dying crowns, ladder fuels, and high surface fuel loadings.

In response to these trends, the U.S. has increased appropriations for wildfire fuel treatment projects through the National Fire Plan and complementary programs (Healthy Forest Restoration Act 2003; Sexton 2006; USDA Forest Service and USDI Bureau of Land Management 2001). Appropriations for fuel treatments have also been awarded through the 2009 American Recovery and Reinvestment Act as an economic stimulus to the national recession. The goals of fuel treatment projects are to reduce wildfire fuels within stands, to provide defensible space around homes and communities, and to create fuel breaks that allow for more aggressive and effective initial attack suppression efforts (Finney and Cohen 2003; Reinhardt and others 2008). Mechanical methods include slash busting, chipping, bundling, piling and burning, as well as pre-commercial and commercial thinning. Prescribed fire is also used as a treatment, often in combination with mechanical methods. Effective treatments result in the removal of woody biomass from treated areas and improved residual stand vigor, which promote resiliency to fire, insect and disease. Fuel treatment projects also reduce fire spread and intensity both inside and outside the portions of the landscape treated (Finney 2001; Finney and others 2007). In most cases, fuel treatment projects are completed at a financial loss; the stumpage value of merchantable trees is usually insufficient to cover the cost of the overall treatment. Moreover, fuel treatment projects are not without controversy with respect to their impact on forest ecological values, even though there is general agreement as to their need (Brown 2008).

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Carbon Dioxide Emissions and Wildfires

For the period 2002-2006, wild and prescribed fire emissions from forests, range and agriculture in the U.S. averaged 4-6 percent of human derived carbon dioxide (CO₂) emissions from fossil fuel sources (Wiedinmyer and Neff 2007). However, the level of emissions varies widely among states and time of year. In Oregon, fire emissions are about 50 percent of the fossil fuel CO₂ emissions (Wiedinmyer and Neff 2007). A similar study estimates emissions from catastrophic wildfire in California during 2001-2007 as equivalent to three and a half years worth of CO₂ emissions from 14 million cars (Bonnicksen 2009). Wiedinmyer and Neff (2007) conclude that very large wildfires in a severe fire season lasting only one or two months can release as much carbon as the annual emissions from the entire transportation or energy sector of an individual state.

Increases in wildfire severity and extent will lead to increases in carbon dioxide (CO₂) emissions to the atmosphere. Simulations of how Oregon's forests will be affected by climate change in Bachelet and others (2001) show that Oregon's forests will accumulate more woody biomass, not less, especially in the eastern region of the state where continued biomass accumulation in the understory increases the risk of uncharacteristically severe wildfire. Nielson (2004) suggests that Oregon's current wildfire risk problem is not only the result of fire suppression efforts, but also the result of an underlying climate signal that has increased biomass accumulation. This signal is expected to continue into the future. In the Pacific Northwest, area burned can be expected to increase despite management efforts to reduce fuel loadings through treatment in fire prone forests (Gedalof and others 2005). As a result, the risk of high severity wildfires in western forests will increase, not decrease, in the future (McKenzie and others 2004). The area in need of fuel treatment far exceeds what is being planned for and accomplished despite increases in federal appropriations. This situation only stands to get worse as climate change leads to more biomass accumulation in western forests (USDA Forest Service 2005). Law and others (2004) conclude that large fire events, such as Oregon's 2002 Biscuit fire can significantly reverse the role forests play in the carbon cycle from being net carbon sink that sequesters atmospheric CO₂ to being a net source of CO₂ to the atmosphere, not only in the year of the fire, but in subsequent years due to continued decomposition of fire-killed material.

The wildfire risk problem can in part be attributed to an excess of stored carbon in the forest as a result of many decades of fire suppression (Hurteau and North 2009; North and others 2009; Stephens and others 2009a). Fuels reduction treatments in general reduce the amount of stored carbon on treated areas and are thus a source of carbon to the atmosphere. Girod and others (2007) concluded that strategies that promote both carbon storage and reduced wildfire risk will need to involve increased fuel treatment efforts that are spatially adjusted to avoid unnecessary reductions in carbon stocks. Despite the fact that fuel treatment practices result in carbon releases back to the atmosphere, several studies conclude that fuel treatment projects can result in a net gain in carbon storage landscape-wide because of the treatment's effect on reducing and avoiding CO₂ emissions from severe wildfires (Bonnicksen 2009; Hurteau and others 2008; North and others 2009; Stephens and others 2009a). Other studies disagree; fuel treatment leads to a net loss of carbon on the forest landscape even when the avoided emissions from uncharacteristically severe wildfire are factored in (Krankina and others 2008; Mitchell and others 2009).

These differing conclusions can be attributed to the fire regime and disturbance return interval of the forest vegetation type being studied and how wildfire risk is assessed. For example, Mitchell and others (2009) concluded that for hemlock-spruce-Douglas-fir forest types of western Oregon, fuel treatment projects fell

at odds with effectively managing forests for long-term carbon storage. This is because extreme weather conditions, not fuel loadings, are the leading cause of high severity wildfires in these forest types. Krankina and others (2008) found a net carbon benefit to treated stands, but only in short fire return interval dry ponderosa pine forests where the removal of non-merchantable understory material was sufficient to reduce wildfire risk.

Unless the surface fuels, understory and ladder fuels found in small, unmerchantable trees are all treated to reduce wildfire risk, the treatment projects will not be effective in reducing wildfire severity and extent (Cram and others 2006; Stephens and others 2009b). There are not many facilities that will take this type of material and when they do, the delivered value of the material is usually not sufficient to cover the costs of its removal and transportation (Mason Bruce & Girard Inc. and others 2006). Recognizing the potential of utilizing forest slash and other residues as a source of biomass energy, thereby displacing fossil fuel use, Oregon's strategy for reducing greenhouse gases included the creation of markets for forest biomass as a significant greenhouse gas mitigation action (Governor's Advisory Group on Global Warming 2004). The question remains though on whether the implementation of fuel treatment projects creates an additional carbon benefit accruing to the treated forest landscape (as the Advisory Group hypothesized), or results in an overall decrease in carbon stores that should be deducted from any displaced CO₂ emissions benefit claims being attributed to biomass energy.

Purpose

The purpose of this study is to properly account for the net balance of carbon storage resulting from a landscape fuel treatment project. On the treated acres themselves, the goal is to reduce or remove biomass, which may reduce on-site carbon stocks, even when continued carbon storage in long-lived wood products and avoided wildfire emissions is accounted for. However, strategically located fuel treatments can reduce fire spread and intensity both inside and outside the portions of the landscape treated. Therefore, the accounting of carbon gains and losses resulting from the fuel treatment project must be calculated in a way that includes the reduction in fire risk to and corresponding change in carbon stores within untreated areas of the landscape.

Quantifying whether a treatment's effect on stored carbon is positive or negative is especially important if the fuel treatment project attempts to seek funding from entities investing in such a project as a means to generate carbon offsets to their CO₂ emissions. If the treatment effect is positive (more carbon is stored on the landscape as a result of treatment), then a carbon offset might be able to be claimed by the project⁶. Clearly, if the opposite is true, then no carbon offset can be claimed. Such a "negative offset" means that there is an emission cost, in terms of carbon released to the atmosphere. But this result does not mean the fuel treatment project is any less effective in its primary purpose—to make forested landscapes more healthy and resilient to wildfire—and as a result, more suited for providing clean water, fish and wildlife habitat, and protecting Oregon's communities from the risk of wildfire.

⁶ Whether or not the amount of carbon benefit can actually be claimed as an offset in a voluntary carbon market or compliance carbon trading program is beyond the study's scope.

Methods

Because wildfire is a chance event, this study estimates the expected carbon stored in forests based on the probability of wildfire on the landscape. Using a simulation modeling approach, expected carbon loss from wildfire on the untreated landscape is estimated and compared to the expected carbon loss from wildfire and treatment for the treated landscape. There are two ways to look at carbon loss. The first is to look at the expected change in carbon stocks; the second is to look at the expected carbon emissions from the landscape. If all affected carbon pools are accounted for, the two measures of carbon loss mirror one another. The expected change in carbon stocks equals expected carbon emissions when both changes are measured in the same units such as CO₂ equivalent. At the time of a wildfire event, carbon loss increases as the intensity of wildfire increases and in all cases, regardless of intensity, wildfire reduces carbon stocks. Only in the case where wildfire does not occur can carbon stocks increase. This study's approach is to simulate all possible wildfire intensities on all possible stand conditions (both treated and untreated) to develop carbon loss functions for each stand condition. Then, by simulating thousands of wildfires on the landscape, a probability surface of wildfire is developed both for the treated landscape and the untreated landscape. The difference in the probability surfaces (treated minus untreated) is a measure of the treatment effect on reducing both the likelihood of wildfire on the landscape given an ignition, and the intensity of wildfire given that wildfire occurs. Simulating carbon loss functions using this probabilistic approach and comparing the results from treated and untreated landscapes quantifies the expected change in carbon stocks resulting from treatment. Table 1 summarizes the major steps for the analysis.

Study Area

The study area is the Drews Creek watershed located within the Goose Lake basin of southern Oregon (fig. 1). The Drews Creek watershed was selected because it contains dry ponderosa pine and mixed conifer forest types at risk of uncharacteristically severe wildfire, is at the beginning stages of fuel treatment planning by the Fremont-Winema National Forest, and is within a collaborative terrestrial sequestration research pilot through the West Coast Regional Carbon Sequestration Partnership⁷. The watershed is approximately 169,200 acres of which approximately 77,500 acres are privately owned and the remaining 91,700 acres are owned and managed by the U.S. Department of Agriculture (USDA) Forest Service.

The Drews Creek watershed encompasses a relatively narrow band of topographical relief. Elevations of the watershed range from 6,400 - 7,900 ft in the northeast portion to 4,200 - 5,000 ft in the valley adjacent to Goose Lake in the southwest. Although slope ranges from 0 - 200 percent, much of the watershed slopes relatively gently with the average slope being 14 percent. The forested area of the watershed is 140,526 acres. Stands dominated by ponderosa pine (*Pinus ponderosa* Laws.) account for about 68 percent of the forest land in the watershed. Approximately 17 percent of the area is in juniper woodlands, and western juniper (*Juniperus occidentalis* Hook.) dominates 26 percent of all forested types, encroaching on the hot dry ponderosa pine sites. Stands dominated by white fir (*Abies* spp.) represent a minor contingent of the landscape, at about 6 percent of

⁷ For more information on WESTCARB, see: <http://www.westcarb.org/>.

Table 1—Steps for modeling wildfire risk, fuel treatments and expected carbon.

Step	Description	Data source	Model
1	Calculate the amount of stored carbon by carbon pool for each untreated stand condition under all possible wildfire intensity conditions, including no fire.	GNN ^a treelist and LANDFIRE fuel model data.	FFE-FVS ^b with fuel model override and FlameAdj keyword.
2	Calculate the amount of stored carbon by carbon pool for each treated stand condition under all possible wildfire intensity conditions, including no fire.	Post treatment FVS treelist output.	FFE-FVS with fuel model override and FlameAdj keyword.
3	Create untreated landscape file.	Slope, Aspect, Elevation, GNN treelist, and LANDFIRE fuel model data; FVS outputs (initial conditions) for Canopy Bulk Density, Canopy Base Height, Crown Closure and Canopy Height.	ArcFuels
4	Create treated landscape file.	Same as Step 3 except use FVS outputs from Step 2 for Canopy Bulk Density, Canopy Base Height, Crown Closure and Canopy Height and switch fuel model to 181 for treated stands.	ArcFuels
5	Conduct repeated landscape simulations of wildfire from a random wildfire ignition for both the untreated and treated Drews Creek landscapes.	Landscape files from Steps 3 and 4.	Randig
6	Calculate conditional burn intensity probabilities for each 90- by 90-meter pixel for both the untreated and treated landscapes.	Output from Step 5.	Randig
7	Calculate the amount of expected stored carbon for each 90- by 90-meter pixel for both the untreated and treated landscapes.	Outputs from Step 1, Step 2 and Step 6.	ArcFuels
8	Calculate and map the expected carbon offset for each 90- by 90-meter pixel; summarize results to get the carbon offset accruing to the treated landscape.	Outputs from Step 7; the offset is treated landscape results minus untreated landscape results.	ArcFuels

^a GNN—Gradient nearest neighbor.

^b FFE-FVS—The Fire and Fuels Extension to the Forest Vegetation Simulator.

the forested acres. Smaller stands of lodgepole pine (*Pinus contorta* Dougl. ex Loud.) as well as small stands of aspen (*Populus tremuloides* Michx.) are scattered across the landscape. Past harvesting activities have significantly reduced the area dominated by large diameter old growth ponderosa pine. Dry grasslands, dry shrub lands and dry meadows comprise nearly one-half of non-forested lands (tree cover less than 10 percent) with the balance being agricultural lands and wet meadows associated with the major streams.

Fuel loadings are variable across the drainage, but follow various gradients. As elevation increases, stands types move from pure low elevation ponderosa pine, to ponderosa pine dominated mixed conifer, in association with white fir, western white pine (*Pinus monticola* Douglas ex D. Don), sugar pine (*Pinus lambertiana* Dougl), and incense-cedar (*Libocedrus decurrens* Torr.), to upper elevation fringes where white fir dominates or more frequently co-dominates with ponderosa pine.

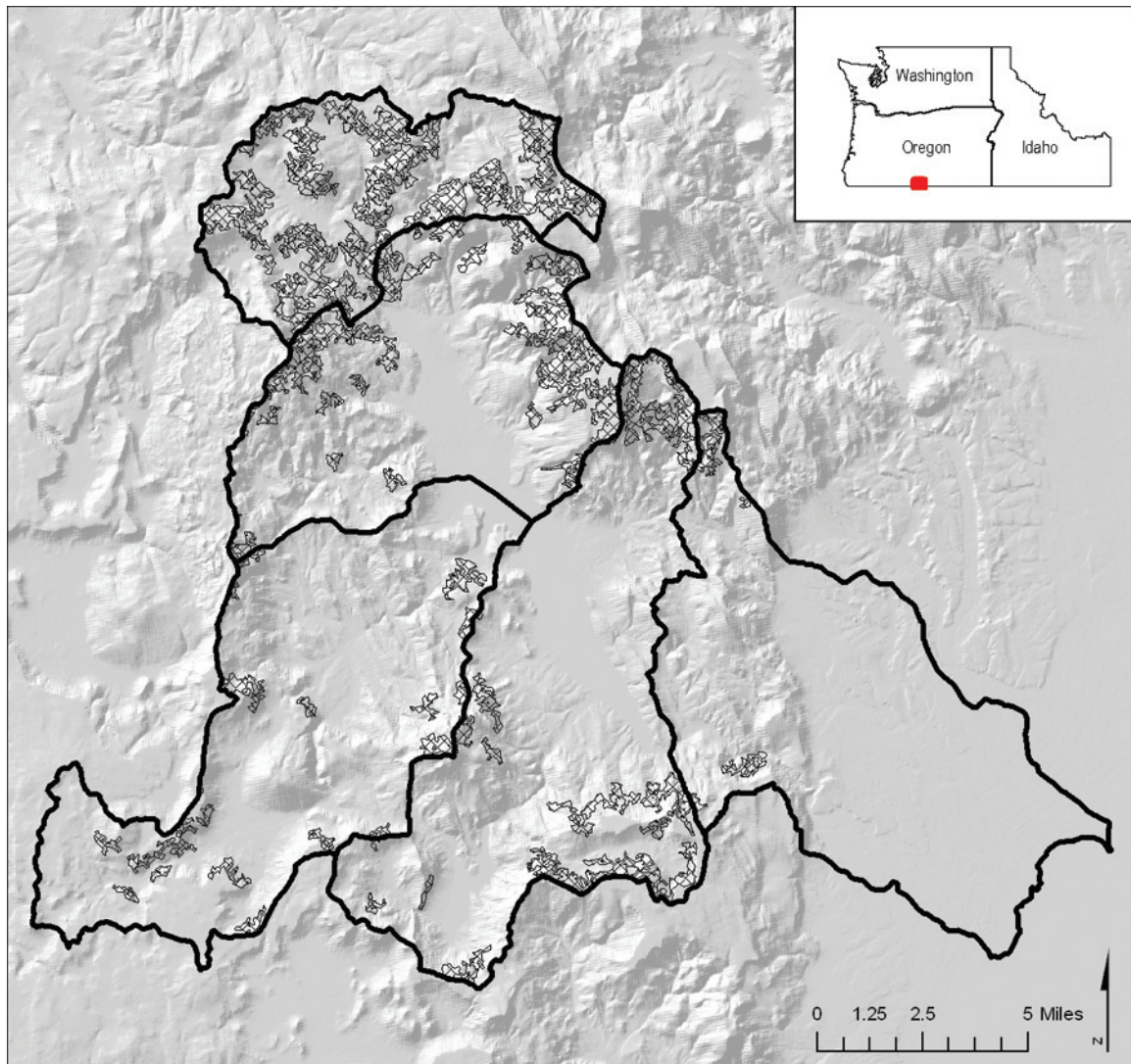


Figure 1—Vicinity and relief map for the Drews Creek Watershed, Fremont-Winema National Forest showing watershed boundaries and treatment units.

Another gradient is aspect, and a third is whether there has been a prescribed burning treatment. Most of the pine dominated stands below 5,500 feet in elevation have received at least one prescribed burn treatment, the exceptions being the Quartz Creek sub-watershed and the Chandler Creek drainage, forming the northern tier of the watershed.

In the low elevation treated pine stands, typical fuel loadings range from 2-5 tons per acre. Untreated pine stands tend to be more variable, averaging 3-15 tons per acre. As white fir joins the stands at low elevations, loadings increase rapidly, particularly where root disease is present. Typical loadings here can range from 15 tons to as high as 50 tons per acre or more if there has been recent disturbance without fuel treatment. For the period of 1949-1999 the watershed has had 688 wildfire ignitions, with an average of fourteen fire starts per year. The high was 38 in 1977 and the low was one in 1963. All fires were actively suppressed. Of these, 88 percent were suppressed at less than 0.25 acres, 10 percent between 0.26 to 9.9 acres with the balance larger. Forty-four fires larger than 10 acres occurred over this period; the total burned for these fires is approximately 9,000 acres.

Spatial Modeling of Wildfire, Fuel Treatments and Expected Carbon Loss

The study used ArcFuels⁸ to automate much of the analyses (Ager and others 2006). ArcFuels is a library of ArcGIS⁹ macros developed to streamline spatial modeling of wildfire behavior, stand growth and yield, and fuel treatments for planning purposes. ArcFuels brings together various data layers (e.g., gradient nearest neighbor (GNN¹⁰) treelists, digital elevation grids, stand polygons, Forest Vegetation Simulator¹¹ (FVS) growth and yield outputs, LANDFIRE¹² fuel model data, slope, and aspect) and processes them in ways that facilitate communication between fire simulation, stand growth and yield, and spatial modeling programs. ArcFuels links the FlamMap¹³ wildfire behavior models with fuels and vegetation data through a Microsoft[®] Office and ArcGIS platform. Carbon stocks were modeled through the Fire and Fuels Extension (FFE) of FVS¹⁴. Specifically, FFE-FVS accounts for the following carbon pools: aboveground total and merchantable live, below ground live and dead, standing dead, dead and down woody debris, forest floor (litter and duff), and understory (shrub and herb). FFE-FVS also accounts for the fate of carbon stored in merchantable material removed—specifically the amount of continued storage in wood products and landfills—as well as the amount emitted for energy and non-energy use (Rebain 2009).

Stand treatments—Stands were selected for treatment based on criteria developed by staff on the Fremont-Winema National Forest. Virtually all stands eligible based on basal area (70 ft² per acre), also met additional distance to road and slope criteria. Pixels selected for treatment were then aggregated into treatment units having a minimum size of 15 acres by first kernel density smoothing the selected pixels, and then retaining only those pixels that exceeded a density threshold. The result was 94 treatment polygons, consisting of 17,740 acres, averaging 175 acres each (fig. 1). The treatment units covered approximately 12.6 percent of the watershed's forestland. Of the 17,740 acres, only 12,825 acres met thresholds for treatment (9.1 percent of the watershed's forestland).

Stands (represented by the imputed GNN treelist data to 30- by 30-meter pixels) that were within treatment polygons were assigned a treatment prescription and the treatment was then simulated in FVS. The treatment prescriptions called for thinning from below to a residual basal area of 70 ft² per acre for mixed conifer or fir dominated stands and 50 ft² per acre for pine dominated stands, followed by slash removal and under burning. The specific parameters for the fuel reduction prescription were chosen based on operational guidelines from the Fremont-Winema National Forest. The treatments were simulated with FVS and consisted of a three-year sequence of thinning from below, site removal of surface fuels, and under burning. Under burning and mechanical treatment of surface fuels was simulated with the FFE-FVS keywords SIMFIRE and FUELMOVE (Reinhardt and Crookston 2003). Fuel treatment prescriptions for thinning from below had no upper diameter limit and specified retention of fire tolerant ponderosa pine and

⁸ For more information on ArcFuels, see: <http://www.fs.fed.us/wwetac/arcfuels/>.

⁹ For more information on ArcGIS, see: <http://resources.esri.com/gateway/index.cfm>.

¹⁰ For more information on gradient nearest neighbor data, see Ohmann and Gregory (2002).

¹¹ For more information on the Forest Vegetation Simulator, see: <http://www.fs.fed.us/fmsc/fvs/>.

¹² Landscape Fire and Resource Management Planning Tools Project. For more information see: <http://www.landfire.gov/>.

¹³ For more information on FlamMap, see Finney (2006).

¹⁴ See pp. 3 through 7 in Rebain (2009) and Hoover and Rebain (2008).

avored the removal of white fir. Surface fuel treatments simulated the removal of 90 percent of the material up to 12 inches. Under burning was then simulated using weather conditions and fuel moisture guidelines provided by fuels specialists on the Fremont-Winema National Forest. The prescription was supported by empirical studies as effective for reducing potential wildfire behavior (Peterson and others 2003; Stephens and Moghaddas 2005; Stephens and others 2009b; van Wagendonk 1996).

Burn probability modeling—We simulated wildfires using the minimum travel time (MTT) fire spread algorithm of Finney (2002) as implemented in a command line version of FlamMap called “Randig” (Finney 2006). The MTT algorithm replicates fire growth by Huygens’ Principle where the growth and behavior of the fire edge acts as a vector or wave front (Finney 2002). Extensive testing over the years has demonstrated that the Huygens’ Principle can accurately predict fire spread and replicate large fire boundaries on heterogeneous wildlands (Knight and Coleman 1993; LaCroix and others 2006; Yohay and others 2009). The MTT algorithm was parallelized for multi-threaded processing making it computationally feasible to perform Monte Carlo simulations of many fires (>100,000). The MTT algorithm is now being applied daily for operational wildfire problems throughout the U.S.¹⁵ and can generate burn probability surfaces for very large (> 2 million ha) landscapes (Ager and Finney 2009; Ager and others 2006; Ager and others 2007). The MTT algorithm assumes constant weather and is used to model individual burn periods within a wildfire rather than continuous spread of a wildfire over many days and weather scenarios.

Relatively few burn periods generally account for the majority of the total area burned in large (e.g. >5,000 ha) wildfires in the western U.S., and wildfire suppression efforts have little influence of fire perimeters during these extreme events. Based on input from forest staff, and supported by historical data from remote automated weather stations, each fire event was simulated as an 8-hour burn period with a 25 mph wind under the fuel moisture conditions listed in table 2. Wind was randomly simulated from three directions (225, 235, and 245 degrees) for each burn period. Ignition locations were random. The target simulated problem fire under these conditions, on average, was 11,000 acres. Randig outputs a vector of conditional burn probabilities (BP_i) for each pixel that represents the probability of a fire at the i^{th} 0.5 m flame length category. Different flame lengths

Table 2—Fuel moisture values used in the wildfire simulations^a.

Parameter	Percent moisture
1 hour	4
10 hour	5
100 hour	7
Live herbaceous	60
Live woody	62

^aPersonal communication. Fire management and silviculture specialists, Lakeview Ranger District, Fremont-Winema National Forest.

¹⁵ See: <http://www.fpa.nifc.gov> and http://wfdss.usgs.gov/wfdss/WFDSS_About.shtml.

are predicted by the MTT fire spread algorithm depending on the direction the fire encounters a pixel relative to the major direction of spread (i.e. heading, flanking, or backing fire) (Finney 2002). The conditional burn probability for a given pixel is an estimate of the likelihood that a pixel will burn given a random ignition somewhere in the watershed under the weather conditions represented in the simulation. Random ignitions were also allowed to originate outside the watershed to include wildfire events that burned into the watershed. The treated and untreated landscapes were simulated with 10,000 wildfires to generate burn probability and intensity (flame length) surfaces at 90 m resolution.

Carbon loss—To quantify the potential effects of wildfire on carbon stocks, each possible stand condition (as represented by the GNN treelist data—both treated and untreated) for each possible wildfire intensity (as represented by flame length category) was burned through FFE-FVS. Each stand condition in the study area was burned within FFE-FVS under a pre-defined surface fire flame length ranging from 0.5 m to 10 m in 0.5 m increments (SIMFIRE and FLAMEADJ keywords). The post-wildfire carbon reports in FFE (FVS_Carbon and FVS_Hrv_Carbon reports) were then examined to determine the amount of carbon in each carbon pool post burning at each flame length. Treatments and wildfire were simulated within the first four years of the simulation; the FFE-FVS outputs from the fifth simulation year were used as the results. The result was a carbon loss function for each stand condition representing all the possible post-wildfire carbon stocks by wildfire intensity class including no wildfire. Carbon loss is defined here as the reduction in post-wildfire carbon stocks for a given wildfire intensity class when compared to the carbon stocks present if no wildfire occurred; the amount reduced being equivalent to CO₂ emissions to the atmosphere from the fire. For treated stand conditions, carbon loss included the sum of carbon loss from treatment and from wildfire. Treatment carbon losses occur as a result of the disposal of non-merchantable material either removed or left on site, carbon losses associated with the end-use and fate of merchantable material removed and from CO₂ emissions from the under burns. The fate of the non-merchantable material removed was not accounted for; it was treated as a CO₂ emission at the time of treatment.

The current configurations of FVS and Randig do not allow for exact matching of fire behaviors. Randig reports total flame length of the surface and, if initiated, crown fire. In contrast, the FVS FLAMEADJ keyword does not allow for specifying a total flame length (surface and crown); rather it allows specification of a flame length for surface fires only. Moreover, FVS FLAMEADJ will not simulate crown fire initiation if it is parameterized with only a fire flame length (except as reported in the potential fire report). To simulate crown fires in FVS, we calculated a critical flame length (representing the threshold flame length between a surface fire and a crown fire) and imposed 100 percent crown consumption (via parameter 3 of the FLAMEADJ keyword) when the surface fire flame length exceeded the critical flame length.

Expected Carbon

The carbon stocks representing the amount of stored carbon post-wildfire (for untreated stand conditions) and post-treatment and post-wildfire (for treated stands) was matched with the burn probability data to calculate expected carbon for each 90- by 90-meter pixel as follows:

$$E[C]_{LS_j} = \left[\sum_{i=0}^{20} [BP_{ij} \times SC_{ij}] \right] + WPC_j \quad (1)$$

where:

$E[C]_{LSj}$ = Expected carbon (mass per unit area) post-wildfire for the j th pixel and
LS = TRT for the treated landscape and NO-TRT for the untreated landscape.

BP_{ij} = Conditional burn probability of wildfire intensity class i reaching the pixel j ; where:

$$\sum_{i=1}^{20} BP_{ij} = BP_j \text{ where } BP_j \text{ is the overall burn probability of wildfire reaching pixel } j$$

BP_{0j} = Conditional probability of no fire = $1 - BP_j$;

$$\text{and } \sum_{i=0}^{20} BP_{ij} = 1$$

SC_{ij} = total stand carbon, post-wildfire of wildfire intensity class i burning in pixel j ; $i=1$ to 20.

SC_{0j} = total stand carbon in pixel j if no wildfire occurs.

WPC_j = carbon stored in wood products from treatment in pixel j .

For the untreated landscape, $WPC_j = 0$ for all j . For treated pixels on the treated landscape, SC_{ij} represents total stand carbon post treatment and post-wildfire for intensity class i burning in pixel j for $i = 1$ to 20 and for treated pixels on the treated landscape, SC_{0j} represents total stand carbon post treatment if no wildfire occurred.

Carbon offset calculations—The expected carbon offset is calculated for each 90- by 90-meter pixel by comparing the expected post-wildfire amount of carbon stored in the pixel post-treatment (if the pixel is treated) for the treated landscape with the amount of carbon stored in the same pixel post-wildfire on the untreated landscape. If the carbon offset is positive—meaning that the amount of carbon stored on the treated landscape is greater than the amount of carbon stored on the untreated landscape—then a positive CO₂ emission reduction benefit occurs as a result of undertaking the treatments.

The expected carbon offset, $E[(\Delta C)]$, for the treated landscape is calculated as follows:

$$E[(\Delta C)] = \sum_{j=1}^n (E[C]_{TRT_j} - E[C]_{NO-TRT_j}) \quad (2)$$

where:

n = is the total number of pixels in the landscape

$E[C]_{TRT_j}$ = is the expected carbon post treatment and wildfire in pixel j ; treated landscape

$E[C]_{NO-TRT_j}$ = is the expected carbon post-wildfire, pixel j ; untreated landscape, and

$E[C]_{TRT_j} - E[C]_{NO-TRT_j}$ = the carbon offset occurring in pixel j as a result of treatment.

$E[(\Delta C)] > 0$ is a necessary condition for the offset to be used as mitigation for CO₂ emissions from an unrelated source. However, if $E[(\Delta C)] < 0$, then the fuel treatment project resulted in more CO₂ emissions (less stored carbon) than if the landscape remained untreated. This does not mean the fuel treatment project should not be implemented; rather, those other benefits of conducting the fuel treatment project (e.g., resource protection, lowering community wildfire risk) come with a net loss of carbon from the landscape to the atmosphere.

Results

Fuels treatment had the desired effect of reducing the likelihood of fire reaching a given pixel as measured by burn probability (figs. 2 and 3; table 3). For untreated stands on the treated landscape, the likelihood of wildfire spreading to untreated stands was also reduced as a result of applying the treatments (fig. 4a). For treated stands, there was a shift in the conditional burn probability distribution making low intensity fires much more likely than if the stands had not been treated, as well as reducing the overall likelihood of wildfire in those stands (fig. 4b). This lowered the average per acre carbon loss from wildfire in post-treated stands when compared to untreated stand conditions (fig. 4b). Comparing the frequency distribution of the wildfire simulations for both landscapes also shows that the fuel treatments were effective in reducing the intensity and extent of wildfire (fig. 5). Average fire size on the treated landscape was 32 percent lower than average fire size on the untreated landscape. Secondly, the largest fire simulated on the treated landscape was 15,000 acres compared to over 19,000 acres for the untreated landscape. In general, the treated landscape experienced a greater number of smaller sized wildfires when compared to the untreated landscape.

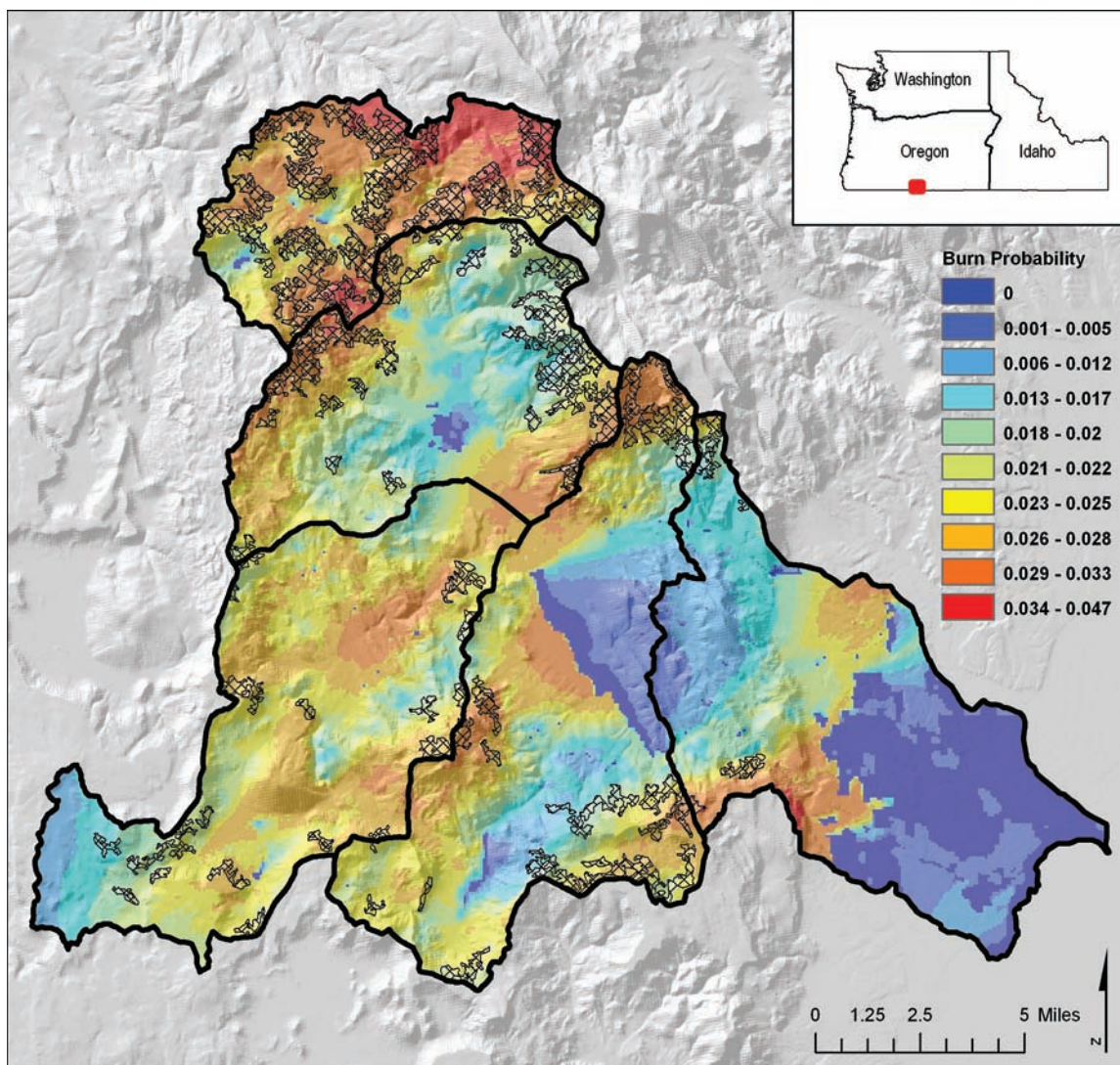


Figure 2—Conditional burn probability map from 10,000 randomly located ignitions and 8-hour burn periods (untreated landscape).

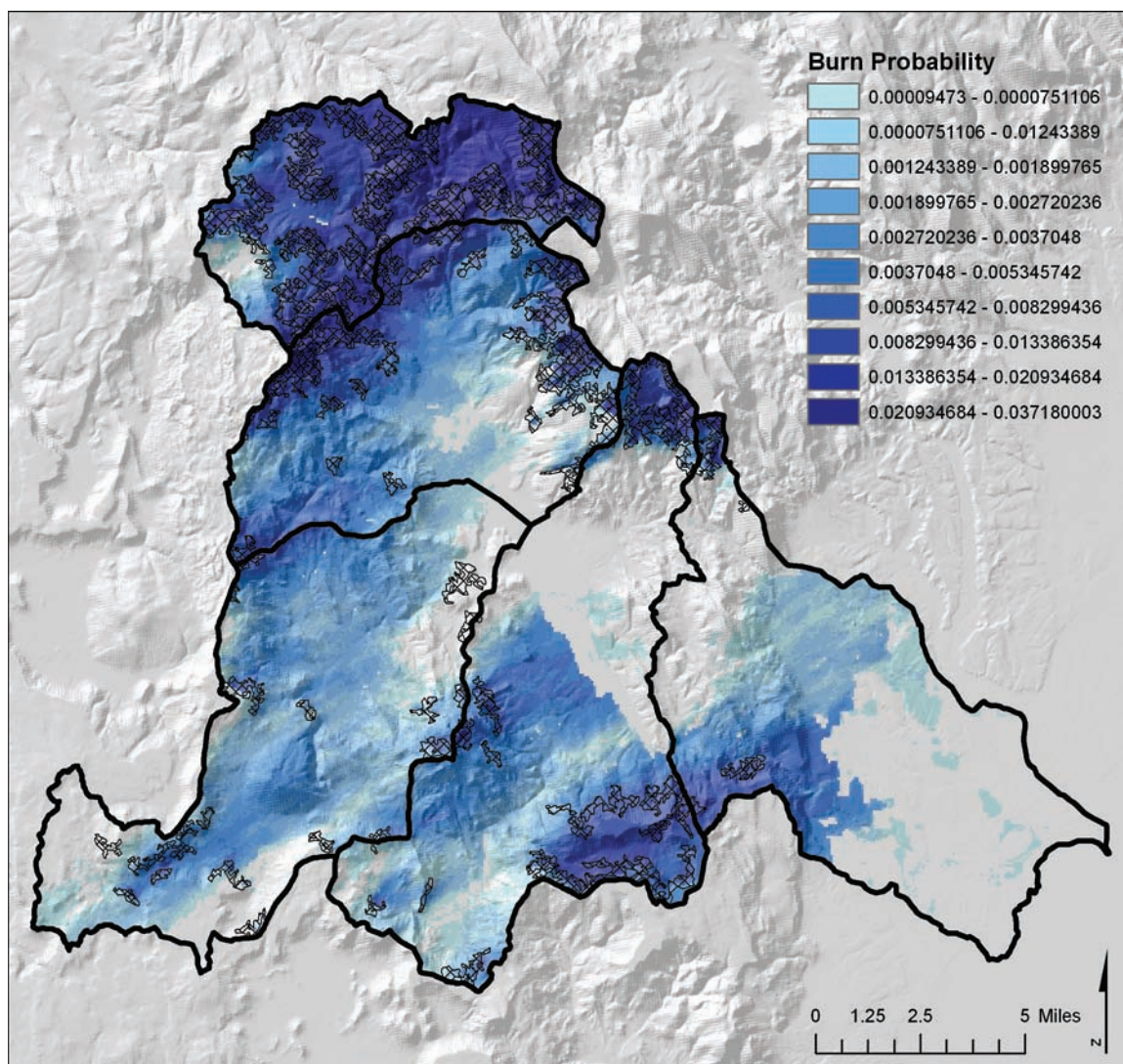


Figure 3—Difference in burn probability between untreated and treated landscape. Areas not shaded within watershed boundary had differences less than 0.0025.

Table 3—Mean overall conditional burn probabilities for Drews Creek—forestland.

	Treated landscape	Untreated landscape	Difference
Treated stands	0.01235	0.02602	−0.01367
Untreated stands	0.01709	0.02106	−0.00397
All stands	0.01665	0.02152	−0.00487

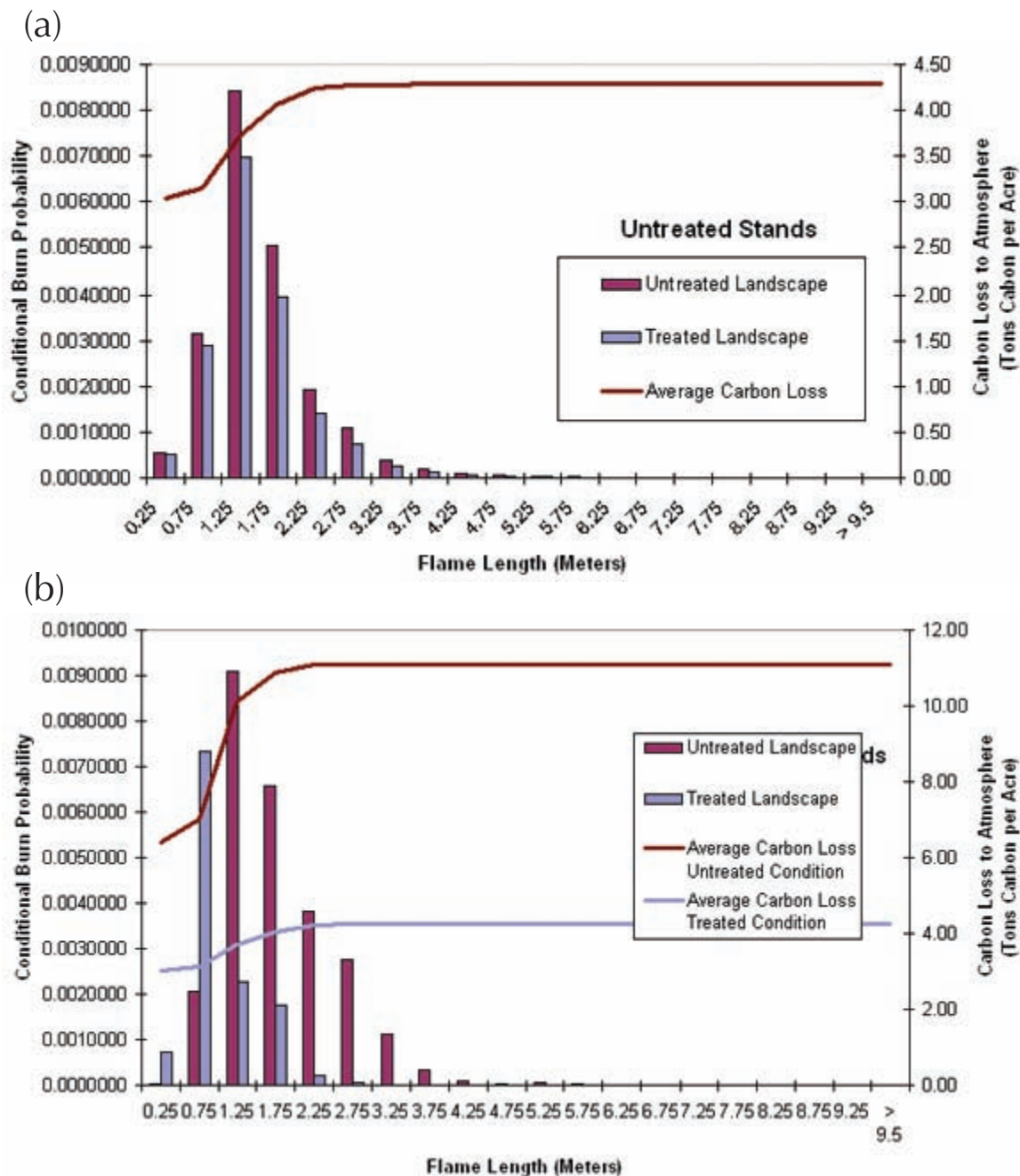


Figure 4—Frequency histograms for burn probabilities for untreated (a) and treated (b) scenarios for the Drews Creek watershed study area.

When compared to the carbon stocks post-wildfire for the same areas on the untreated landscape, fuels treatment resulted in a net carbon loss to the atmosphere of −303,458 tons (table 4) (−23.7 tons per treated acre). The expected carbon stocks within the untreated area of the treated landscape did increase to a small degree (3,536 tons; or 0.027 tons per untreated acre) as a result of the treatment's effect of reducing the likelihood that wildfire reaches the untreated stands. However, the cost in terms of carbon released to the atmosphere as a result of treatment was overwhelming with a net, negative carbon offset, $E[(\Delta C)] = -299,622$ tons (table 4) (−2.13 tons per forested acre).

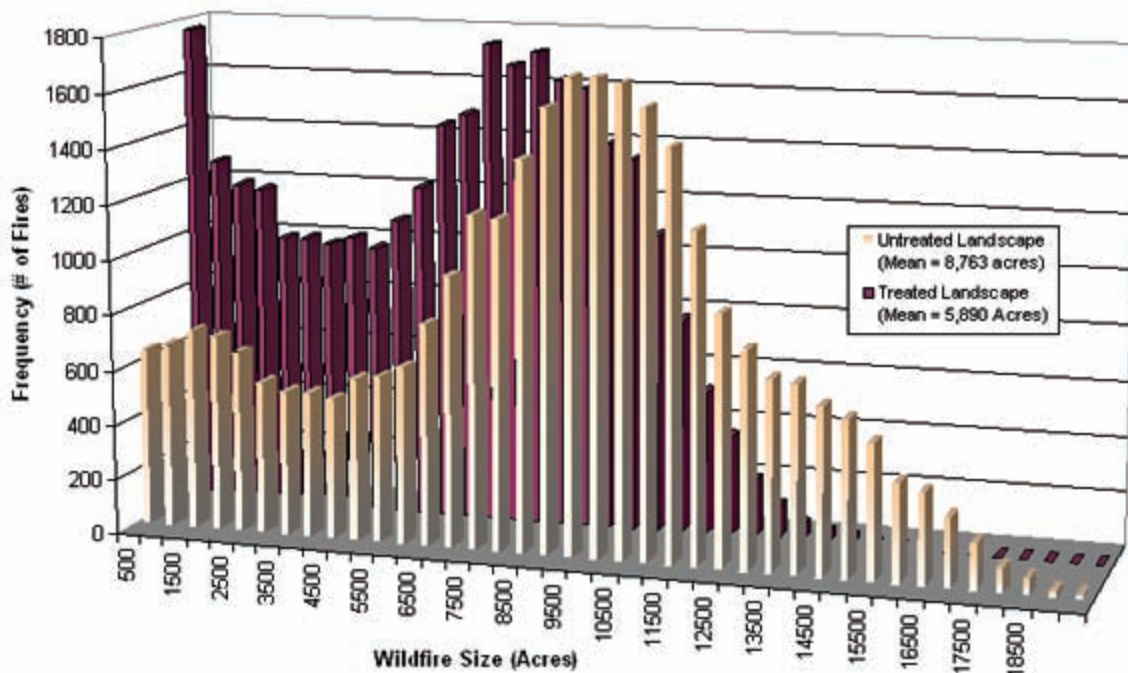


Figure 5—Frequency histogram of simulated fire sizes for untreated and treated scenarios for the Drews Creek watershed study area.

Table 4—Expected stored carbon immediately after wildfire—Drews Creek—forestland

	Treated landscape	Untreated landscape	Difference
<i>short tons carbon</i>			
Treated stands ^a	538,940	842,398	−303,458
Untreated stands	2,961,484	2,957,948	3,536
	OFFSET		−299,622

^aThis is the area selected for treatment on the treated landscape but remained untreated on the untreated landscape. The treated stand area plus the untreated stand area equals the total forestland area.

Biomass removed through thinning from below and movement of the excess material (slash) resulting from harvest activities removed 215,071 tons of carbon (16.8 tons per treated acre) representing 19.1 percent of the total biomass in treated stands. Of this amount, 159,440 tons (74 percent) was emitted to the atmosphere (12.4 tons per treated acre) with the remaining 55,631 tons (26 percent) remaining stored in long-lived wood products (4.3 tons per treated acre). Under burning emitted another 111,893 tons carbon (8.7 tons per treated acre) representing 13.3 percent of the total biomass in treated stands. In total, carbon lost to the atmosphere from the fuel treatment activity totaled −271,333 tons carbon (−21.2 tons per treated acre) (table 5). In comparison, only an expected 3,700 tons (0.21 tons per acre) of avoided carbon loss accrued to the treatment polygons as a result of the treatment's effect of reducing both the likelihood and intensity of wildfire in treated stands. Similarly, only 3,087 tons of expected avoided carbon loss accrued to the untreated polygons (0.025 tons per acre) as a result of the treatment's effect of reducing the likelihood of wildfire, for a total benefit of 6,787 tons of expected

Table 5—Expected carbon emissions^a—Drews Creek—forestland.

Emission source	Treated landscape	Untreated landscape	Difference
<i>short tons carbon</i>			
Merchantable material removed From treatment, but not stored	–41,884	0	–41,884
Non-merchantable material removed from thinning treatment	–62,796	0	–62,796
Non-merchantable material removed from FUELMOVE treatment	–54,760	0	–54,760
Total, thinning activity	–159,440		–159,440
Prescribed fire in treatments	–111,893	0	–111,893
Total, all treatment practices	–271,333		–271,333
Wildfire treated ^b stands	–157	–3,857	3,700
Wildfire non-treated stands	–8,936	–12,023	3,087
		OFFSET	–264,546

^a Negative sign indicates a loss of stored carbon to the atmosphere.

^b This is the area selected for treatment on the treated landscape but remained untreated on the untreated landscape. The treated stand area plus the untreated stand area equals the total forestland area.

carbon loss avoided (0.048 tons per forested acre). The net expected carbon loss accruing to the treated landscape when compared to the untreated landscape is –264,546 tons (–1.9 tons per forested acre) carbon (table 5)¹⁶.

Discussion

The Law of Averages

The question is—if the implementation of fuels treatments within the Drews Creek watershed had the beneficial effect of reducing the likelihood of wildfire intensity and extent as simulated in this study, why is the expected carbon offset from fuels treatment so negative? The answer lies in the probabilistic nature of wildfire. Fuels treatment comes with a carbon loss from biomass removal and prescribed fire with a probability of 1. In contrast, the benefit of avoided wildfire emissions is probabilistic. The law of averages is heavily influenced that given

¹⁶ FVS does not account for all carbon losses as emissions and as a result the offset as calculated in table 4 (from comparing carbon stock changes) does not balance with the offset calculated in table 5 (from comparing carbon emission changes).

a wildfire ignition somewhere within the watershed, the probability that a stand is not burned by the corresponding wildfire is 0.98 (1 minus the average overall conditional burn probability in table 3). The simulations also included all possible wildfire scenarios from one random ignition within the Drews Creek watershed under the severe weather and fuel moisture conditions that *could* result in the problem fire. But, in many of the simulations, the problem fire did not occur (fig. 5).

Thus, the expected benefit of avoided wildfire emissions is an average that includes the predominant scenario that no wildfire reaches the stand. And if the predominate scenario for each stand is that the fire never reaches it, there is no avoided CO₂ emissions benefit to be had from treatment. So even though severe wildfire can be a significant CO₂ emissions event, its chance of occurring and reaching a given stand relative to where the wildfire started is still very low, with or without fuel treatments on the landscape. Further, when wildfire does occur, the immediate effect is to transfer the stored carbon on the landscape from the live tree pool to the standing dead tree pool. So, most of the carbon stored before wildfire is still there after wildfire, and the amount of carbon loss compared to the stored carbon before wildfire is still relatively small. Had this study included the continued carbon loss over time from the decomposition of the dead tree pool post-wildfire, then the total avoided wildfire emissions would have been greater.

Life Expectancy of Fuel Treatments

The carbon offset result of –299,622 tons carbon (–2.13 tons per forested acre) is the carbon offset of avoiding the possibility of a severe wildfire based on a single wildfire ignition under extreme weather and fuel moisture conditions. Our study results show that for any given ignition in the year after the completion of fuel treatments, the expected avoided carbon loss from one wildfire ignition is 6,787 tons carbon. But the Drews Creek watershed experiences on average, 14 wildfire ignitions a year. For example, if 1/3 (i.e., say 5) of the 14 ignitions per year for Drews Creek occurred during the severe weather and fuel moisture conditions used in this study and independence is assumed in the wildfire outcomes from one ignition to another, then the expected avoided carbon loss from the same fuel treatment investment (and treatment carbon loss) is 33,935 (=5*6,787) tons carbon¹⁷. This amount is still not enough benefit to make the carbon offset positive for the year following the completion of the fuel treatment project.

But, the fuel treatment project is actually an investment in reducing wildfire risk over an extended period of time beyond the year following treatment. If the life expectancy of the implemented fuel treatments is at least 9 years, then the expected carbon offset becomes positive. That is, if for each year, the fuel treatments avoid an expected 33,935 tons of carbon loss to the atmosphere, then 305,415 (=9*33,935) tons of expected carbon loss is avoided after 9 years for the same –299,622 treatment carbon loss investment¹⁸. While the carbon offset from fuel treatments is clearly negative for any one ignition in the year immediately

¹⁷ This is a simplifying assumption used for illustrative purposes. If each random ignition wildfire outcome is an independent event—meaning the spread and intensity of the wildfire from the second ignition is not influenced by how the wildfire burned from the first ignition—the overall burn probability of wildfire reaching the stands from 5 random ignitions on the landscape is 5 times the probability of it reaching the stand from one ignition. Any dependency would lower this result, but the concept still holds.

¹⁸ Again, this assumes independence between wildfire outcomes from one year to the next. In this case, this is a conservative estimate. It may be that the burn probability landscape intensifies—meaning the probability of wildfire not reaching a stand (1-BP) decreases if the problem fire event does not occur in the preceding year.

following the completion of treatments, it may become positive within the course of the shelf life of the treatment's effectiveness in reducing wildfire risk. Further, accounting for the consequences of continued decomposition from the in-stand dead tree pools and continued sequestration from the live tree pool not lost to wildfire as a result of treatment improves the carbon offset potential of the fuel treatment. While not accounted for in this study, the expected carbon benefit from the fuel treatment project would be better reflected as the cumulative expected avoided carbon loss and improved carbon sequestration gain over time from avoiding the problem fire from multiple ignitions in multiple years after treatment.

Future Work

This study had several limitations. First, the treatment design did not explicitly minimize the carbon loss from conducting the fuel treatment while at the same time maintaining the same level of effectiveness in reducing the risk of catastrophic wildfire. Better utilization of the non-merchantable material removed in products that continue to store carbon would reduce the carbon cost of treatment. Second, the analysis does not account for the continued loss of carbon post-wildfire from decomposition of burned material; nor does the study account for the continued growth and corresponding sequestration that occurs both in treated stands (where fire severity and extent is reduced) and in untreated stands (where the chance of wildfire reaching them is reduced) outside of the treatment areas. Third, we did not convert the conditional burn probabilities of wildfire occurring given an ignition on the landscape to the absolute probability of wildfire occurring. This step would take into account the probability of ignition and could take into account other factors such as the improved effectiveness of suppression afforded by treatment. Finally, modeling the shelf life of fuel treatments using burn probability maps for more than one year following treatment that take into account the wildfire outcomes in previous years might better reveal the cumulative carbon offset of conducting the fuel treatment project.

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