

How Fuel Treatment Types, Locations, and Amounts Impact Landscape-Scale Fire Behavior and Carbon Dynamics

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Abstract—When managing for fire across a large landscape, the types of fuel treatments, the locations of treatments, and the percentage of the landscape being treated should all interact to impact not only potential fire size, but also carbon dynamics across that landscape. To investigate these interactions, we utilized a forest growth model (FVS-FFE) and fire simulation software (FlamMap, Randig), integrated through GIS software (ArcMap9.3), to quantify the impacts that varied landscape-scale fuel treatments have on burn probability, fire size, short-term carbon loss, and long-term carbon storage. Thirteen fuel treatment scenarios were simulated on a 42,000 hectare landscape in the Klamath Mountains of northern California including one untreated, three proposed by the U.S. Forest Service, and nine that were spatially optimized and developed within the Treatment Optimization Model in FlamMap. The nine spatially optimized scenarios varied by treatment type (prescribed fire, mastication, and thin + burn) and landscape intensity (10 percent, 20 percent, and 30 percent of the landscape treated). Each treatment scenario was subjected to 10,000 simulated wildfires with random ignition locations in order to develop burn probability and mean fire size for each scenario, which subsequently impacted long-term carbon storage projections.

Our results show that both fire behavior metrics (mean burn probability, fire size) and carbon dynamics (short-term carbon loss, long-term carbon storage) are indeed highly dependent upon the treatment type, spatial arrangement, and proportion of the landscape treated. The thin + fire treatment at 20 percent treatment intensity most reduced fire size while prescribed fire at 10 percent landscape intensity least reduced fire size and did not differ from the untreated landscape. However, prescribed fire treatments resulted in the greatest onsite long-term carbon storage across the landscape after 50 years. Treating 20 percent of the landscape appears to be the optimal treatment landscape intensity for both reducing fire size and for maximizing long-term onsite carbon storage; treating beyond 20 percent of the landscape produces diminishing returns in both parameters.

Introduction

Various fuel management strategies can be employed to reduce the intensity and subsequent severity of wildland fires in forest ecosystems (Stephens 1998; Stratton 2004; Agee and Skinner 2005; Schmidt and others 2008). A large body of work on stand-scale fuel treatments exists that demonstrate their ability to reduce fuel loading (Sackett 1975; Stephens 1998; Vaillant and others 2009; Large 2010; Hamma 2011), limit initiation of crown fires (Martinson and Omi 2003; Murphy and others 2007; Vaillant and others 2009), and slow rates of spread (Stephens 1998; Vaillant and others 2009).

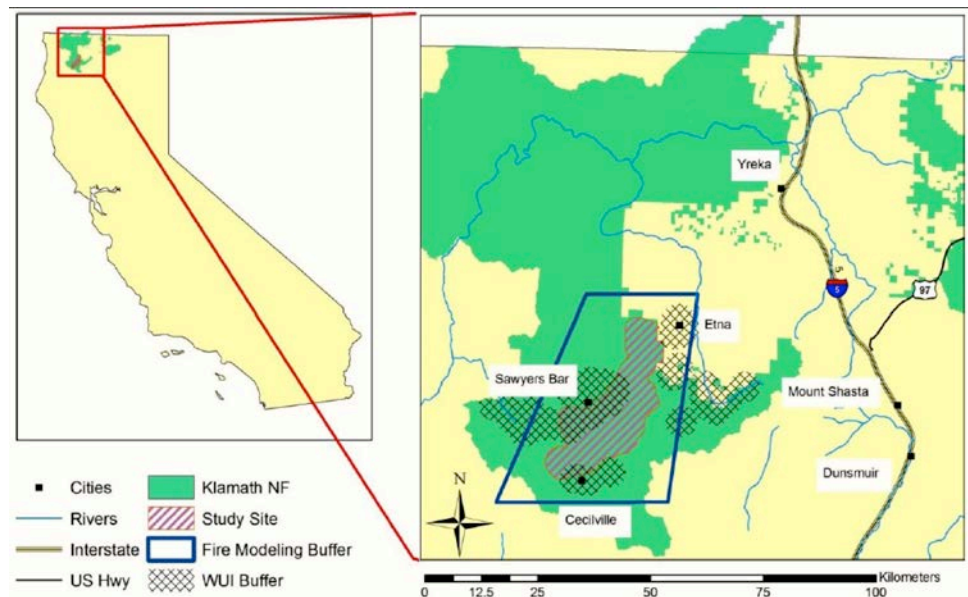
However, while critical to an individual stand's resiliency to fire, isolated fuel treatments may have little impact on the spread of fire across the landscape (Finney and others 2005). Therefore, land managers across the western US are focusing on landscape-scale vegetation management strategies to alter fuel conditions and subsequently protect both the natural and the built environment (Sexton 2006; Weatherspoon and Skinner 2006; Reinhardt and others

2008; Collins and others 2010). To date, landscape-level fire dynamics has received considerably less scientific inquiry than stand-level studies. Existing work, however, suggests that the treatment type, spatial arrangement, and landscape intensity (percentage of the landscape being treated) of various treatment strategies can impact the size and severity of wildfires (Stratton 2004; Ager and others 2007; Finney and others 2007; Schmidt and others 2008; Ager and others, 2010b; Moghaddas and others 2010).

In contrast to the benefits fuel treatments provide, they can also adversely impact various ecosystem services, including carbon sequestration and storage (Tiedemann and others 2000; Dicus and others 2009), which are of growing concern in the fire management community because of the potential to influence global climates and the potential financial implications of developing carbon markets (Westerling and others 2006; Hamilton and others 2007; Mignone and others 2009). Stand-level simulations suggest that alterations in short-term carbon emissions and long-term carbon storage do occur following fuel treatments (Hurteau and North 2009; Large 2010; Reinhardt and Holsinger 2010; Hamma 2011; North and Hurteau 2011), with the effects dependent upon the ecosystem and treatment type (Reinhardt and others 2010; Wiedinmyer and Hurteau 2010; Hurteau and others 2011).

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Figure 1—Location of the study site, which included the Eddy Gulch Late Seral Reserve on the Klamath National Forest and a larger buffer used in fire modeling simulations.



In this study, we simulated how various landscape-level fuel treatment strategies simultaneously impacted both fire size and carbon dynamics on a fire-prone 42,000 ha landscape in the Klamath Mountains of northern California that consisted primarily of montane mixed-conifer forest. Specifically, we compared the burn probability, fire size, onsite short-term carbon loss (after 5 years) and long-term onsite carbon storage (after 50 years) on an untreated landscape to three fuel treatment scenarios proposed in a Klamath National Forest management plan and to nine spatially optimized treatment scenarios that varied in treatment type, spatial arrangement, and landscape intensity.

Methods

Study Site

The study site was a 42,000-hectare area on the Salmon River Ranger District of the Klamath National Forest in Siskiyou County, California (123 4.72 W 41 1554 N), which consisted of the Eddy Gulch Late Successional Reserve (LSR), which was implemented to protect critical habitat and adjacent residential communities (USDA Forest Service and DOI Bureau of Land Management 1994), and also a buffer around the LSR (Figure 1). Elevation ranged from approximately 300 m to 2,500 m, with steep terrain crossed by numerous ridges and watercourses (USDA Forest Service 2010). Climate in the area is Mediterranean, with hot, dry summers and cold, wet winters.

Vegetation consists largely of multi-layered, multi-aged forests. Douglas-fir (*Pseudotsuga menziesii* Mirb.) and ponderosa pine (*Pinus ponderosa* C. Lawson) dominate at lower elevations. Douglas-fir, white fir (*Abies concolor* Gord. and Glend.), and red fir (*Abies magnifica* A. Murray) dominate at higher elevations where moisture is more abundant (Taylor and Skinner 1998).

Historic mean fire return intervals were ~12 years, but due to fire exclusion in the previous century, fire return intervals have increased to an average of ~22 years (Taylor and Skinner 1998; Taylor and Skinner 2003). At present, as much as 73 percent of the area within the LSR is at risk for passive or active crown fire activity under extreme weather conditions (USDA Forest Service 2010).

Treatment Scenarios and Modeling Procedure

We assessed 13 fuel treatment scenarios, including an untreated scenario, three scenarios derived from a Forest Service proposal to treat fuels within the LSR (U.S. Forest Service 2010; hereafter KNF-proposed treatments), and nine spatially optimized treatment scenarios that varied by treatment type, spatial arrangement, and landscape intensity (percent of the total landscape treated). Figure 2 depicts the overall procedure used to generate the various GIS landscapes, fire outputs, and carbon outputs. A simplified methodology is described here; a more detailed methodology for this project is found in Osborne (2011).

Forest inventory and analysis (FIA) data for the Klamath National Forest were obtained from the USFS Region 5 Remote Sensing Lab (USDA Forest Service 2009), which also provided a digital elevation model, fuel model data, and GIS vegetation attribute layers (canopy base height, crown bulk density, crown height, and height to live crown). We used these data to build an ArcFuels project (Vaillant and others 2013) within ESRI's ArcGIS software (V. 9.3.1; ESRI 2009). We then used the ArcFuels project to build a GIS landscape that served as our untreated control landscape as well as the initial point for developing landscapes for the 12 other treatment scenarios.

The KNF-proposed treatments for the LSR were composed of mechanical units and prescribed fire units (Figure 3; USDA Forest Service 2010). The mechanical units, which included mastication treatments and thin + burn treatments along ridge tops, covered 9 percent of the study site. The

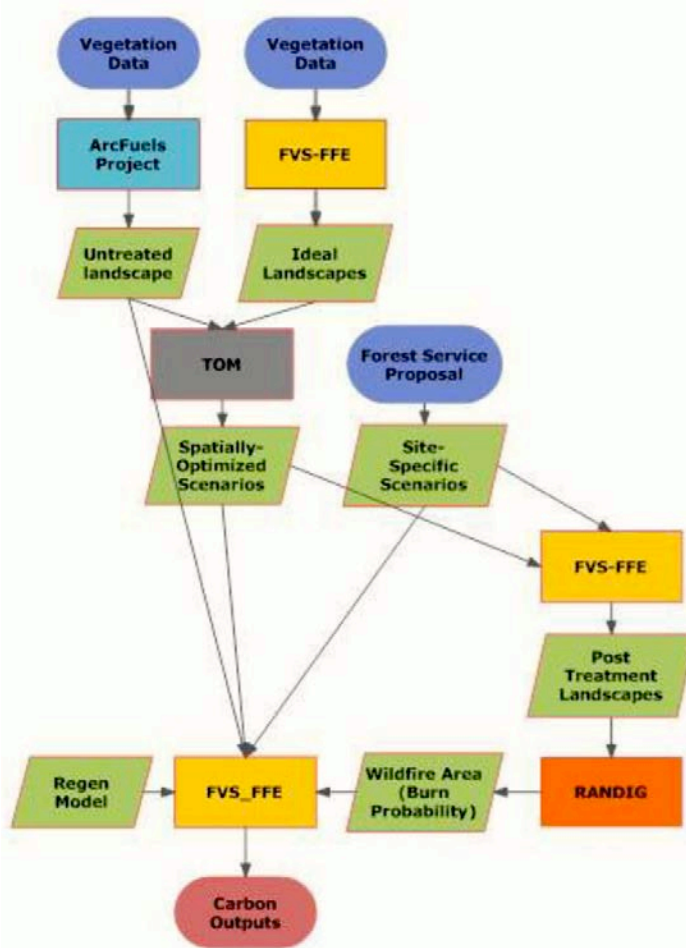


Figure 2—General flow chart representing the major inputs and processes used to generate fire size and carbon outputs.

prescribed fire units, located primarily on south and south-west aspects, covered 17 percent of the study site. The total design, which combined all mechanical and prescribed fire units, covered 26 percent of the study site.

We also created nine spatially optimized fuel treatment scenarios utilizing the Treatment Optimization Model (TOM) within FlamMap (v 3.0) (Finney 2006; Finney 2007). These nine scenarios included three treatment types (prescribed fire, mastication, and thin + burn), each at 3 landscape intensities (10 percent, 20 percent, and 30 percent of the landscape treated; Figure 4). The percentage of area

treated represented logical increases, which closely matched the percentage of the landscape treated in each of the KNF-proposed treatment scenarios, and which also mirrored those used in previous work with landscape fuel treatment arrangements on the Klamath National Forest (Schmidt and others 2008).

For the spatially optimized treatments, we generated our “ideal” landscapes for TOM with the FVS-Fire and Fuels Extension (FFE; Inland California variant) (Rebain 2010) within ArcFuels (Vaillant and others 2013) so as to implement treatment vegetation alterations in all stands within our study site. We did this for each of the three treatment types (prescribed fire, mastication, and thin + burn), resulting in three ideal landscapes. We assigned fuel models to each stand based on pre-treatment conditions and expected post-treatment conditions for each type of treatment (Fites-Kaufman and others 2007), basing our custom mastication fuel model on an average of slash fuel models as described by Knapp and others (2008).

We used FireFamilyPlus (v 4.1) (Rocky Mountain Research Station Fire Lab and Systems for Environmental Management 2002) and historical fire weather data from the Blue Ridge Remote Automated Weather Station (RAWS) to develop our fuel moisture parameters and fire weather conditions (Table 1). Moderate values for wind and temperature were based on 20-year (1984–2004) RAWS data for May through October, discussions with Klamath National Forest fire management staff, and values used by Large (2010), whose work was conducted in the Klamath Mountains. The fuel moisture and weather parameter values used for prescribed fire simulations approximate the 50th percentile level, which previous work has used to represent moderate fire behavior (Ager and others 2010b; Large 2010). Given constant wind and moisture parameters, the TOM used a minimum travel time algorithm to calculate arrival time contours and the paths where fire moves fastest across the landscape (Finney 2002; Finney 2004; Finney 2006), and then placed treatments to optimally reduce the overall landscape ROS given the area treated (Finney 2007).

The FlamMap treatment location outputs created with the TOM were converted into ArcGIS raster files within ArcFuels. We then used these raster layers to assign treatments to stands based on the percentage of stands covered by treatment cells when we overlaid the stand polygon layer with a treatment raster.



Figure 3—Landscape fuel treatment scenarios proposed in a management plan at the study site.

Figure 4—Example of placement of spatially optimized treatments with increasing landscape intensity, which was determined by the Treatment Optimization Model in FlamMap. 3.0. The thin + burn fuel treatment is shown.

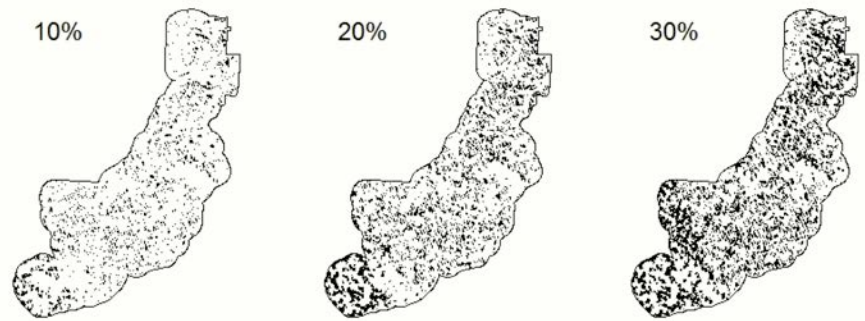


Table 1. Weather Scenario.

Weather Parameter	Rx Fire (50th percentile)	Wildfire (97th percentile)
Windspeed (km hr ⁻¹)	16.1	42.3
Wind Direction (Azimuth)	238	238
Temperature (C°)	21.1	32.2
Fuel Moisture (%)		
1-hr (<.64cm)	4	2
10-hr (0.64-2.54cm)	5	3
100-hr (2.54-7.62cm)	10	5
1000-hr (>7.62cm)	11	8
Duff	30	10
Live Woody	77	70
Foliage	100	80

We placed the untreated landscape and each of the post-treatment landscapes into Randig (Mark Finney, U.S. Forest Service Rocky Mountain Research Station), a command line version of FlamMap to determine burn probability for each pixel (raster cell) of the study site for a given scenario, which was calculated as the number of times the pixel burned divided by the number of ignitions in the simulation (10,000). The weather conditions for the Randig simulations were at the 97th percentile. We used burn periods ranging from 600 to 1100 minutes for each of the 10,000 random ignitions per scenario in order to create a distribution of fire sizes that mirrored an observed distribution of extreme growth events on the Klamath National Forest.

To incorporate future wildfire into the long-term FVS-FFE simulations, we used burn probability to represent areas with the highest chance of experiencing wildfire post-treatment. Stands with a mean burn probability over 0.0067 were assigned wildfires 5 years post-treatment in subsequent long-term carbon simulations in FVS-FFE. We chose this threshold based on the percentage of the untreated landscape (33.86 percent) that received a wildfire assignment. We chose wildfires at 5 years post-treatment to account for the range in which we expected treatments to maintain maximum effectiveness before needing retreatment.

After assigning wildfire locations and creating a tree regeneration model, we completed a separate FVS-FFE simulation for each of the 13 scenarios (1 untreated, 3 KNF-proposed, and 9 spatially optimized designs). These FVS-FFE simulations used the same weather conditions for prescribed fire (50th percentile) and wildfire (97th percentile) as previous simulations.

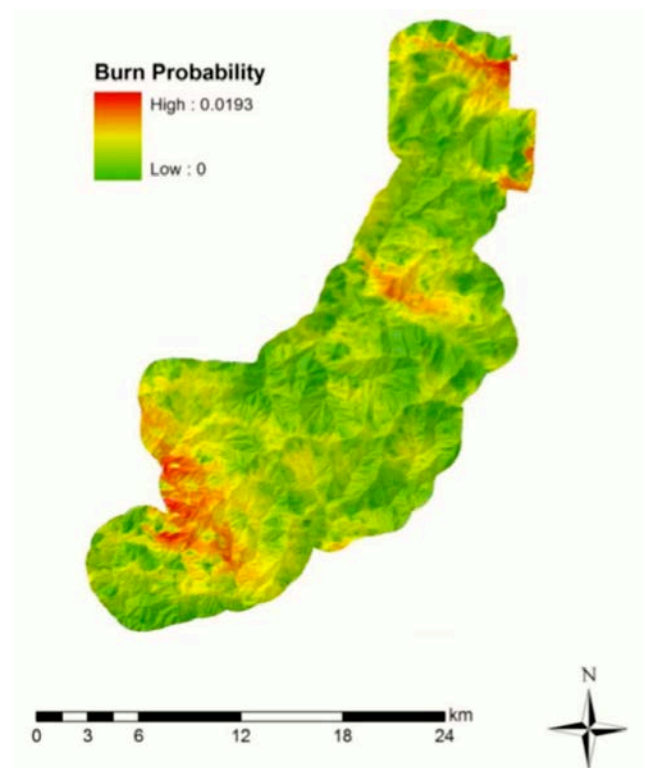


Figure 5—Burn probability (number of times a pixel burned /number of ignitions) in the untreated landscape. Burn probability was also calculated for all treatment scenarios.

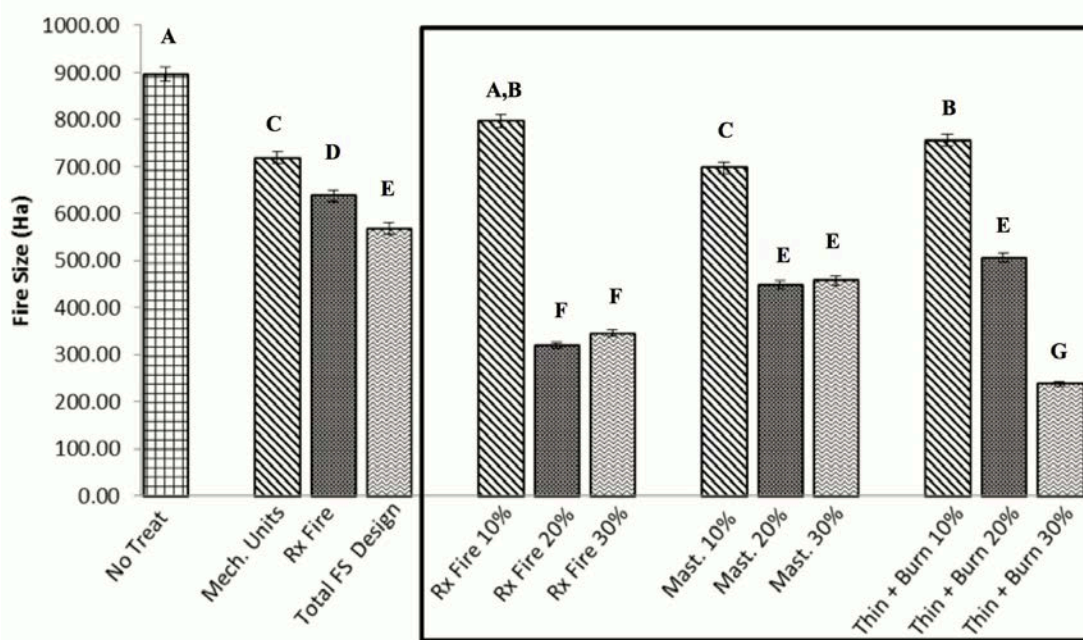


Figure 6—Mean fire size (at 5 years) for each treatment scenario. Scenarios that share a letter have mean values that did not significantly differ from one another at $\alpha = 0.05$. Treatments inside the solid box are spatially optimized; treatments outside the box are treatments proposed in a management plan at the study site.

After completing the 13 FVS-FFE simulations, we used the FFE carbon report to compile short-term carbon loss from fuel treatments, short-term carbon loss from wildfire (5 years post-treatment), and long-term carbon storage (50 years post-treatment) for each treatment scenario. We considered the onsite total stand carbon as the sum of the following carbon pools: aboveground live and dead, belowground live and dead, forest floor (litter and duff), herbs, shrubs, and dead/down woody debris. The carbon reports also include carbon emissions due to fire (it did not distinguish between prescribed fire and wildfire), which we grouped with harvested carbon as the carbon lost from our site.

Statistical analysis for mean burn probability and carbon outputs were precluded because the outputs represent the entire population. We statistically analyzed the mean fire size using a Kruskal-Wallis non-parametric test and a Dunn's method for median separation at pooled alpha level of 0.05 with individual Bonferroni alphas of 0.00064. This individual alpha was derived by dividing the pooled alpha of 0.05 by 78, the total number of possible pairwise comparisons between the 13 scenarios.

Results

Areas with higher burn probability tended to be clumped as opposed to being scattered across the landscape (Figure 5), which was anticipated given localized areas of steep topography and of high fuel loading and continuity. As expected, the untreated landscape had the highest mean burn probability of all scenarios (0.0057).

Figure 6 illustrates mean fire size for each of the scenarios. The mean fire size (for 10,000 random ignitions in each scenario) was significantly larger in the untreated landscape than in all treated scenarios except the prescribed fire treatment type at the 10 percent landscape intensity ($p < 0.001$). Mean fire size among the KNF-proposed treatment scenarios decreased significantly ($p < 0.001$) with increasing landscape intensity, with the largest mean fire size present under the prescribed fire scenario (719.39 ha) and the smallest under the total design scenario (349.56 ha). Mean fire size across the spatially optimized treatment scenarios was highly variable. Prescribed fire at the 10 percent treatment intensity had the largest mean fire size (719.39 ha⁻¹), which was not significantly different from the untreated landscape (Figure 6). The thin + burn treatment at the 30 percent intensity significantly ($p < 0.001$) reduced fire size more than any other treatment scenario (238.31 ha⁻¹).

Figure 7 illustrates onsite short-term carbon loss in each of the scenarios, which was calculated as treatment-induced carbon loss + wildfire emissions (5 years post-treatment). With no treatment, the landscape did not experience short-term carbon loss from treatments, but lost 6.24 Mg ha⁻¹ of carbon via emissions during the wildfire simulated five years post-treatment. As expected, increasing landscape intensity reduced carbon emissions from wildfire, but also increased onsite treatment-induced carbon loss. The relationships were not equal however. As the proportion of the landscape treated increased, the treatment-induced carbon loss grew more rapidly than decreases in carbon lost from wildfire emissions. This was true for all treatment types except spatially optimized mastication treatments, which did not have any treatment-induced losses since they did not include thinning or prescribed fire.

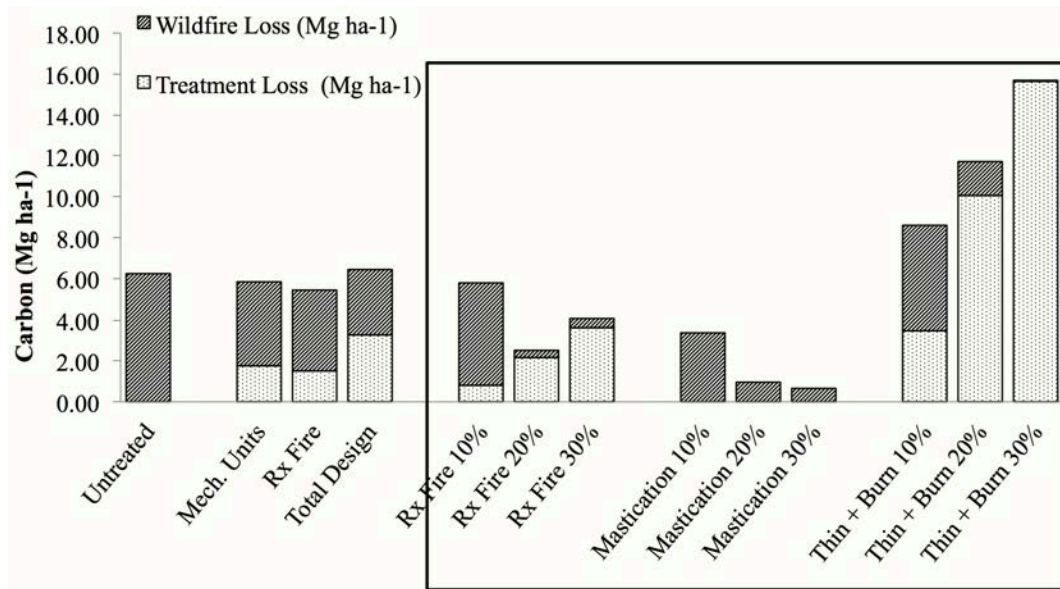


Figure 7—Short-term (at 5 years), onsite carbon losses (Mg ha^{-1}) for each treatment scenario. Stacked bars for wildfire and for treatment-induced carbon losses represent total onsite carbon loss for each scenario. Treatment-induced losses include prescribed fire emissions and vegetation removed in thinning operations. Treatments inside the solid box are spatially optimized; treatments outside the box are treatments proposed in a management plan at the study site.

Short-term carbon loss (treatment-induced + wildfire emissions) for the spatially optimized treatments was highly variable and depended upon treatment type and landscape intensity (Figure 7). Of all spatially optimized treatment designs, mastication at the 30 percent treatment intensity had the lowest short-term carbon loss (0.65 Mg ha^{-1}) and thin + burn at the 30 percent treatment intensity had the largest short-term carbon loss (15.72 Mg ha^{-1}).

Figure 8 illustrates onsite long-term carbon storage (50 years post-treatment). Of all treatments, the spatially optimized prescribed fire only scenario at 20 percent landscape intensity had the largest long-term carbon storage ($370.63 \text{ Mg ha}^{-1}$). For the spatially optimized treatments, the smallest long-term storage was with thin + burn at the 10 percent treatment intensity ($356.04 \text{ Mg ha}^{-1}$) and the greatest long-term carbon storage level was with prescribed fire at the

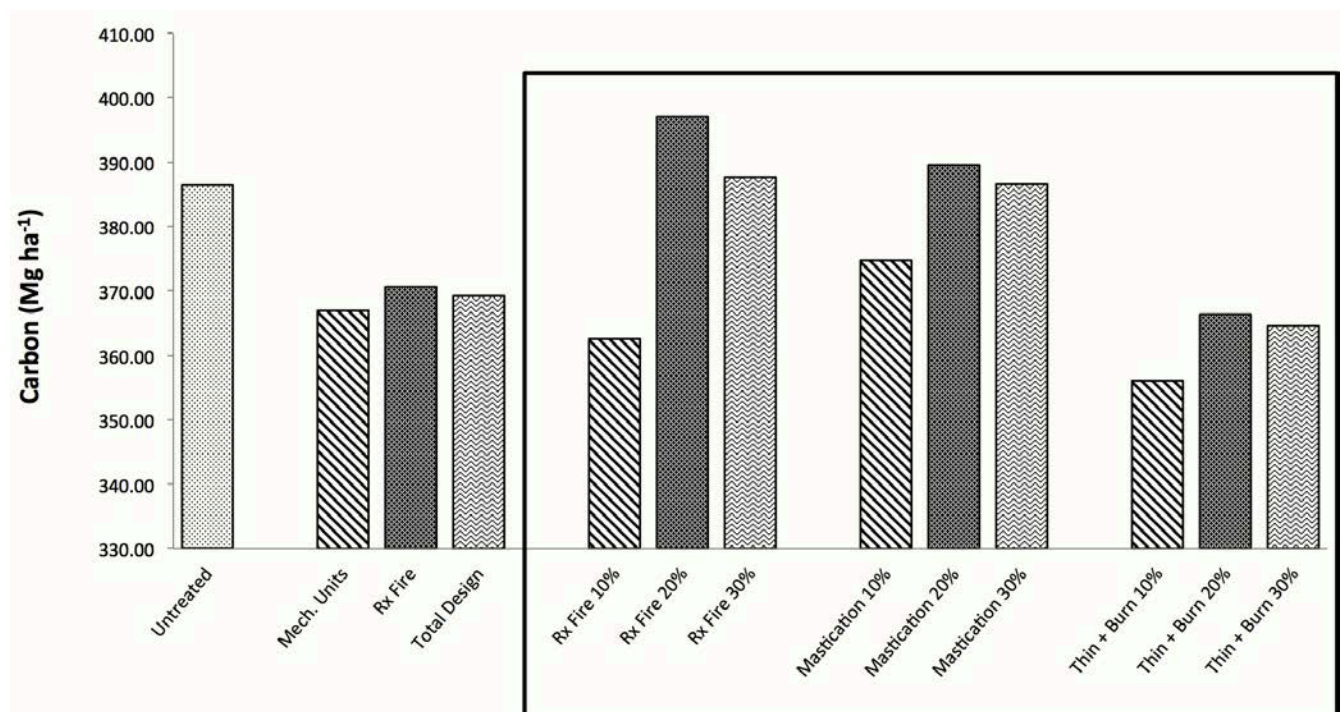


Figure 8—Long-term (at 50 years), onsite carbon storage (Mg ha^{-1}) for each of treatment scenarios. Treatments inside the solid box are spatially optimized; treatments outside the box are treatments proposed in a management plan at the study site.

20 percent treatment intensity ($397.06 \text{ Mg ha}^{-1}$), which was larger than the amount of long-term carbon storage on the untreated landscape. For all spatially optimized treatment types, the long-term carbon storage increased from 10 percent of the area treated to the 20 percent of area treated, but then decreased from 20 percent to 30 percent of the area treated (Figure 8).

Discussion

The complex nature of modeling requires accepting a number of assumptions, including constant weather, a defined burn period, the accuracy of fire spread algorithms, and the accuracy of the growth and yield models. However, all the treatments were subject to the same assumptions, resulting in outputs that should be looked at as relative comparisons between treatments rather than precise predictive values. Our location represents an individual set of fuel loading values, topographic features, and assumed weather parameters, and therefore our results may not be representative of other locations. However, the process utilized here could be utilized on other landscapes to determine the potential impacts varied landscape-scale fuel treatment scenarios have on fire behavior and wildfire exposure.

Our results clearly show that landscape-scale fuel treatments can reduce potential wildfire exposure across the landscape (as measured by burn probability), dependent on treatment type, spatial arrangement, and proportion of the landscape being treated. Treatment type appeared to have less influence on the overall effectiveness of a fuels management strategy than did the proportion of the landscape being treated and the spatial arrangement of those treatments.

At the lowest treatment intensity, mean fire size in the KNF-proposed mechanical treatment design was equal to or significantly lower ($p < 0.001$) than all spatially optimized treatments at the 10 percent landscape intensity (Figure 5). However, as the treatment intensity increased, the KNF-proposed designs no longer outperformed the spatially optimized treatment designs at the analogous treatment intensity. The strong performance of the KNF-proposed treatments at the lowest treatment intensities is likely due to spatial arrangement. The KNF-proposed treatments effectively compartmentalized ignitions due to being placed on ridgetops and their linear nature, which did not allow a fire to flank around the treatment units into untreated corridors. In contrast, the spaces between the spatially optimized treatments at the lowest landscape intensity could have been sufficient to allow development of a heading fire. The changing effectiveness in the spatially optimized designs with landscape intensity confirms previous studies on landscape-scale fuel treatments (Finney 2001; Schmidt and others 2008; Ager and others 2010b).

Like fire size, short-term on-site carbon loss varied widely with treatment type, spatial arrangement, and landscape intensity (Figure 7), a fact that has not been examined in previous studies. Long-term carbon storage values showed

similar patterns across treatment intensities for all treatment types, but the specific values varied between arrangement and treatment type (Figure 8).

The results indicate that if onsite short-term carbon loss and long-term onsite carbon storage are concerns for land managers, fuel treatments that include the combination of thin + burn treatments may not be desirable (Figures 7 and 8). Short-term losses of this treatment is most likely due to the removal of trees up to 71 cm DBH during commercial thinning and the slash left from thinning activities increased surface fuel loading, thus increasing the amount of carbon released during prescribed fire (North and others 2009; Tao and Allen 2010). These results are consistent with short-term stand-level analysis of this treatment type (Stephens and others 2009). Thin + burn units did have the lowest area impacted by wildfire fire at the 30 percent treatment intensity, resulting in reduced carbon loss from wildfire emissions (Figure 7). This result is consistent with stand-level studies that show reductions in carbon loss from wildfire following thin + burn treatments (Finkral and Evans 2008; Hurteau and others 2008; Hurteau and North 2009). However, the reduction in carbon emissions from wildfire at our level of simulation was not sufficient to offset the large onsite losses from thinning and prescribed fire emissions.

The mechanisms that altered short-term carbon loss in the thin + burn scenarios also altered long-term carbon storage. The thinning activity removed large trees that account for the majority of carbon storage, immediately reducing carbon storage on the landscape. The thinning activity also removed healthy, rapidly growing trees (Nowak and Dwyer 2007), reducing the rate of carbon sequestration, and resulting in a slower recovery to pre-treatment carbon storage levels. Increasing the percentage of the area treated should increase storage by reducing the area that experiences wildfire, thus reducing emissions from fire and improving sequestration by preventing the death of vigorously growing trees (Hurteau and North, 2009; Stephens and others 2009; Hurteau and North 2010). However, in this study, the loss in carbon sequestration rate and storage from thinning was greater than the increased carbon that resulted from reduced wildfire.

For minimizing onsite short-term carbon loss, mastication treatments appear to be the most effective due to there being no harvested carbon and no prescribed fire carbon emissions. As the area treated with mastication increased, the carbon loss decreased due to less area being affected by wildfire, resulting in very low short-term carbon loss for mastication at the 30 percent treatment intensity (Figure 7). Over 50 years, the mastication treatments do not have the largest carbon storage but are capable of increasing storage beyond the level of the untreated landscape (Figure 8). A probable cause for this is the removal of the young, vigorously growing trees. Though large trees are the largest pool of carbon, smaller, more rapidly growing trees are a large source of sequestration, which influences storage levels over time (Nowak and Dwyer 2007). Removing large numbers of intermediate and small trees does not alter current storage, but can alter future storage by reducing the present sequestration rate (Hurteau

and North 2009; Large 2010). However, these small trees are often suppressed, so their removal may allow for the remaining trees to increase growth rates through reduced competition, allowing the long-term onsite storage under this treatment type to outperform the proposed site-specific treatment scenarios (Figure 8). Increasing mastication treatment landscape intensity reduced the area burned in wildfire (Figure 6), subsequently reducing carbon loss from wildfire emissions and maintaining storage by reducing large tree mortality (Hurteau and North 2009; Stephens and others 2009; Hurteau and North 2010). However, the reduction in small trees slowed sequestration rates sufficiently to limit carbon storage at year 50, resulting in lower carbon accumulation rates and ultimately lower carbon storage at the 30 percent treatment intensity when compared to the 20 percent treatment intensity.

Spatially optimized prescribed fire treatments demonstrated an inverse relationship between treatment-induced carbon emissions and wildfire-induced carbon emissions (Figure 7). The relationship is not linear however, indicating that if spatially optimized, the reductions in wildfire-induced emissions were large early, but became smaller as the landscape intensity increased. In this study, it appears that the balance point between increasing emissions from prescribed fire and decreasing emissions from wildfire is at the 20 percent landscape intensity. Balancing the treatment-induced emissions with wildfire-induced emissions resulted in the 20 percent landscape intensity having the smallest short-term carbon loss of the prescribed fire treatment scenarios (Figure 7).

Over a 50-year cycle, prescribed fire at the 20 percent landscape intensity had the largest pool of carbon storage of all treatment designs and intensities (Figure 8). Prescribed fire reduced surface fuels and protected large trees from experiencing wildfire mortality, thereby creating fire-resistant stand structures (Hurteau and North 2009; Hurteau and North 2010). This is similar to thin + burn treatments but without the large tree removal or increased slash fuels prior to burning (Stephens and others 2009). When compared to mastication treatments, prescribed fire scenarios lost more carbon in the short-term, but did not remove as many of the small to medium trees, and therefore did not reduce the sequestration rate, allowing for the long-term carbon storage level to increase more rapidly than in mastication treatments, more than compensating for the loss of carbon from the prescribed fire. At the 20 percent treatment intensity, the reduction in wildfire-induced emissions and saving of large trees due to reduced area experiencing wildfire balanced the treatment-induced carbon emissions, while increasing to the 30 percent treatment intensity caused sufficient increase in treatment-induced loss to reduce the long-term storage level.

The KNF-proposed treatments (USDA Forest Service 2010) all experienced a short-term loss of carbon that was close in value to the untreated landscape (Figure 7). Of note is the amount of carbon lost from wildfire (Figure 7), which was not as strongly influenced by treatment intensity as it was when treatments were arranged in spatially optimized patterns. This illustrates that though the KNF-proposed

treatments in the LSR may be more practical to implement than the spatially optimized designs, they were not as effective at reducing the area that experienced wildfire (Figure 6), and as such, were not as effective at reducing short-term carbon loss from wildfires (Stephens and others 2009).

Over 50 years, all KNF-proposed treatment scenarios had lower carbon storage than the untreated landscape and similar or lower carbon storage than all optimized designs at the analogous treatment intensities (Figure 8). An explanation for this is that the limited ability of these treatments to influence wildfire area resulted in a reduced ability of these treatments to protect large trees from wildfire. This resulted in high mortality of mature trees during wildfire, removing the largest source of carbon storage over a larger portion of the landscape (Nowak and Dwyer 2007; Hurteau and others 2011). Just as with the spatially optimized treatment designs, the carbon storage was greatest at the 20 percent treatment intensity (prescribed fire), indicating that as treatment intensities increase past the medium treatment intensity (~20 percent), the prescribed fire-induced carbon emissions and vegetation removals outweigh the protection of mature trees from wildfire and reductions in wildfire carbon emissions.

Overall, the medium treatment intensity (20 percent of the landscape) appears to be the best treatment intensity for maximizing onsite long-term carbon storage. For each treatment type and arrangement, the 20 percent intensity had the largest long-term carbon storage pool. However, across treatment types and arrangements at the 20 percent intensity, the amount of carbon in the storage pools was not equal (Figure 8). This indicates that if long-term carbon storage is a concern for land managers, once the treatment type and design are selected, the percentage of the landscape treated should not exceed 20 percent. In our study site, this result is valuable because it indicates that the more practical site-specific KNF-proposed treatments can minimize onsite short-term carbon loss and maximize long-term carbon storage at the same treatment intensity (Figures 7 and 8).

Finally, it should be noted that this work only considered on-site carbon dynamics and did not consider off-site storage of carbon such as wood used in building construction. Future work on carbon cycling over the short and long term should take a more life cycle approach to the problem, tracking carbon that may be stored offsite and accounting for other short-term carbon emissions stemming from the implementation of fuel treatments.

Another consideration in the interpretation of this study is the implementation of wildfire only one time (5 years post treatment) during the 50-year cycle. Over 50 years, it is likely that more fire would be present on the landscape (Taylor and Skinner 2003) and one would therefore need to recursively implement fire simulations on the landscape, accounting for the impacts previous fires would have on fire spread and intensity as well as carbon emissions. Doing this would be possible using the Randig and FVS programs in a repetitive loop, assigning fire based on burn probabilities generated from the previously burned landscape. The implementation of such a process was logistically impractical for this study given the time consuming nature of the modeling

(each combination of Randig and FVS simulation took 20 to 24 hours). However, such a process could create a more complete picture of the duration of fuel treatment influence on carbon storage across a landscape of this scale.

Acknowledgments

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References

- Agee, J. K. and C. N. Skinner (2005). "Basic principles of forest fuel reduction treatments." *Forest Ecology and Management* 211(1): 83-96.
- Ager, A. A., A. J. McMahan, and others (2007). "A simulation study of thinning and fuel treatments on a wildland-urban interface in eastern Oregon, USA." *Landscape and Urban Planning* 80(3): 292-300.
- Ager, A. A., N. M. Vaillant, and others (2010). "A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure." *Forest Ecology and Management* 259(8): 1556-1570.
- Bradshaw, L. S. and E. McCormick (2000). *FireFamily Plus user's guide*, US Department of Agriculture, Forest Service, Rocky Mountain Research Station Fort Collins, CO.
- Collins, B. M., S. L. Stephens, and others (2010). "Challenges and approaches in planning fuel treatments across fire-excluded forested landscapes." *Journal of Forestry* 108(1): 24-31.
- Dicus, C., K. Delfino, and others (2009). "Predicted fire behavior and societal benefits in three eastern Sierra Nevada vegetation types." *Fire Ecology* 5(1): 67.
- Dicus, C. A. (2009). "Changes to simulated fire behaviour and societal benefits after two levels of thinning in a mixed-conifer wildland-urban interface community." *Proceedings of the Royal Society of Queensland*, The 115: 37.
- Finkral, A. and A. Evans (2008). "The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest." *Forest Ecology and Management* 255(7): 2743-2750.
- Finney, M. A. (2002). "Fire growth using minimum travel time methods." *Canadian Journal of Forest Research* 32(8): 1420-1424.
- Finney, M. A. (2004). "Landscape fire simulation and fuel treatment optimization." *Methods for integrated modeling of landscape change*: 117-131.
- Finney, M. A. (2006). "An overview of FlamMap fire modeling capabilities." *Proceedings of the Fuels Management-How to Measure Success*: 213-220.
- Finney, M. A. (2008). "A computational method for optimising fuel treatment locations." *International Journal of Wildland Fire* 16(6): 702-711.
- Finney, M. A., C. W. McHugh, and others (2005). "Stand-and landscape-level effects of prescribed burning on two Arizona wild-fires." *Canadian Journal of Forest Research* 35(7): 1714-1722.
- Finney, M. A., R. C. Seli, and others (2008). "Simulation of long-term landscape-level fuel treatment effects on large wildfires." *International Journal of Wildland Fire* 16(6): 712-727.
- Fites-Kaufman, J., A. Reiner, and others (2007). "Fuel Treatment effectiveness and effects monitoring in the Pacific Southwest Region."
- Hamma, C. C. (2011). "Effects of Wildland-Urban Interface Fuel Treatments on Potential Fire Behavior and Ecosystem Services in The Central Sierra Nevada Mountains Of California."
- Hurteau, M. and M. North (2008). "Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wild-fire scenarios." *Frontiers in Ecology and the Environment* 7(8): 409-414.
- Hurteau, M. D. and M. L. Brooks (2011). "Short-and long-term effects of fire on carbon in US dry temperate forest systems." *BioScience* 61(2): 139-146.
- Hurteau, M. D., G. W. Koch, and others (2008). "Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets." *Frontiers in Ecology and the Environment* 6(9): 493-498.
- Hurteau, M. D. and M. North (2010). "Carbon recovery rates following different wildfire risk mitigation treatments." *Forest Ecology and Management* 260(5): 930-937.
- Hurteau, M. D., M. T. Stoddard, and others (2011). "The carbon costs of mitigating high-severity wildfire in southwestern ponderosa pine." *Global Change Biology* 17(4): 1516-1521.
- Knapp, E., M. Busse, and others (2008). *Masticated fuel beds: custom fuel models, fire behavior, and fire effects. Final Report to Joint Fire Science Program, Project 05-2-2-20.*
- Large, J. A. (2010). "Effects of Wildland Urban interface Fuel treatments on Fire Behavior and Ecosystem Services in the Klamath Mountains of California." *Master's Thesis*, California Polytechnic State University, San Luis Obispo.
- Long, L. L. (2011). "Eddy Gulch Late-Successional Reserve Landbird Survey Report 2009-2010."
- Martinson, E. J., P. N. Omi, and others (2002). *Performance of fuel treatments subjected to wildfires*, Citeseer.
- Mignone, B. K., M. D. Hurteau, and others (2009). "Carbon offsets, reversal risk and US climate policy." *Carbon balance and management* 4(1): 1-6.
- Moghaddas, J. J., B. M. Collins, and others (2010). "Fuel treatment effects on modeled landscape-level fire behavior in the northern Sierra Nevada." *Canadian Journal of Forest Research* 40(9): 1751-1765.
- Murphy, K., T. Rich, and others (2007). "An assessment of fuel treatment effects on fire behavior, suppression effectiveness, and structure ignition on the Angora Fire. USDA Forest Service, Pacific Southwest Region." *Gen. Tech. Rep. R5-TP-025*: 1-38.

- North, M., M. Hurteau, and others (2009). "Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions." *Ecological Applications* 19(6): 1385-1396.
- North, M. P. and M. D. Hurteau (2011). "High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest." *Forest Ecology and Management* 261(6): 1115-1120.
- Nowak, D. J. and J. F. Dwyer (2007). *Understanding the benefits and costs of urban forest ecosystems. Urban and community forestry in the northeast*, Springer: 25-46.
- Osborne, K. J. (2011). "Simulated Effects of Varied Landscape-Scale Fuel Treatments On Carbon Dynamics And Fire Behavior In The Klamath Mountains Of California."
- Rebain, S. (2009). "The fire and fuels extension to the Forest Vegetation Simulator." Addendum to RMRS-GTR-119. USDA Forest Service and ESSA Technologies Ltd.
- Reinhardt, E. and L. Holsinger (2010). "Effects of fuel treatments on carbon-disturbance relationships in forests of the northern Rocky Mountains." *Forest Ecology and Management* 259(8): 1427-1435.
- Reinhardt, E. D., R. E. Keane, and others (2008). "Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States." *Forest Ecology and Management* 256(12): 1997-2006.
- Sackett, S. S. (1975). "Scheduling prescribed burns for hazard reduction in the southeast." *Journal of Forestry* 73(3): 143-147.
- Schmidt, D. A., A. H. Taylor, and others (2008). "The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range, California." *Forest Ecology and Management* 255(8): 3170-3184.
- Sexton, T. (2006). *US Federal fuel management programs: reducing risk to communities and increasing ecosystem resilience and sustainability*. Andrews, PL, Butler, BW (comps), *Fuels Management—How to Measure Success: Conference Proceedings*. Portland, OR.
- Stephens, S. L. (1998). "Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests." *Forest Ecology and Management* 105(1): 21-35.
- Stephens, S. L., J. J. Moghaddas, and others (2009). "Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest Publication No. 143 of the National Fire and Fire Surrogate Project." *Canadian Journal of Forest Research* 39(8): 1538-1547.
- Stratton, R. D. (2004). "Assessing the effectiveness of landscape fuel treatments on fire growth and behavior." *Journal of Forestry* 102(7): 32-40.
- Tao, Y. and W. R. Allen (2010). "Fuel Loading and the Potential for Carbon Emissions from Fire Following Two Shelterwood Harvest Treatments in Southern Ohio." *Genomics and Applied Biology* 1.
- Taylor, A. H. and C. N. Skinner (1998). "Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA." *Forest Ecology and Management* 111(2): 285-301.
- Taylor, A. H. and C. N. Skinner (2003). "Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains." *Ecological Applications* 13(3): 704-719.
- Tiedemann, A. R., J. O. Klemmedson, and others (2000). "Solution of forest health problems with prescribed fire: are forest productivity and wildlife at risk?" *Forest Ecology and Management* 127(1): 1-18.
- USDA Forest Service. (2009). *Vegetation Inventory: Data by Forest Download Page*. Region 5 Remote Sensing Laboratory. Updated December 2009.
- Vaillant, N. M., A. A. Ager, and others (2013). "ArcFuels User Guide and Tutorial: for use with ArcGIS 9."
- Vaillant, N. M., J. Fites-Kaufman, and others (2009). "Effect of fuel treatments on fuels and potential fire behavior in California, USA, national forests." *Fire Ecology* 5(2): 14-29.
- Weatherspoon, C. P. and C. N. Skinner (1996). *Landscape-level strategies for forest fuel management. Sierra Nevada ecosystem project: final report to congress*.
- Westerling, A. L., H. G. Hidalgo, and others (2006). "Warming and earlier spring increase western US forest wildfire activity." *science* 313(5789): 940-943.
- Wiedinmyer, C. and M. D. Hurteau (2010). "Prescribed fire as a means of reducing forest carbon emissions in the western United States." *Environmental science and technology* 44(6): 1926-1932.