EFFECT OF FUEL TREATMENTS ON CARBON FLUX DURING A WILDFIRE USING SATELLITE IMAGERY: OKANOGAN-WENATCHEE NATIONAL FOREST

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ABSTRACT

Forests are one of the largest stores of terrestrial carbon and can be a significant source of carbon during wildfire events. To mitigate the severity of fires and corresponding carbon flux, forest managers can utilize a variety of fuel treatments including tree harvesting and prescribed burning. The relative effect of fuel treatments on carbon flux from a 70,000-ha fire, the Tripod Complex fire, in north central Washington State was evaluated. Ground-based measurements to determine forest biomass were done in ten treatment units inside the Tripod Complex fire perimeter. The biomass measurements were compared to normalized difference vegetation index and gross primary productivity, along with others, derived from MODIS and Landsat imagery to evaluate the change in carbon sequestration rates of the ecosystem, both before and after the fire. Carbon dioxide emissions from the wildfire were also calculated. On average, the ten treatment areas were found to emit 71% less CO_2 m^{-2} during the fire when compared to the emissions from the total fire area. Treatment areas were also found to retain higher rate of primary productivity, on average 120 g C m^{-2}, than the remainder of the fire. While it is not feasible to treat entire forests, in the future the effect fuel treatments have on carbon flux should be considered.

INTRODUCTION

Forests play a large role in carbon sequestration, by sequestering 77 to 82% of atmospheric carbon (IPCC 2001). Wildfire activity is expected to increase due to years of fire suppression and global climate change (Westerling et al. 2006). Forests can emit large amounts of carbon dioxide during wildfire events (Murray et al. 2003), and their ability to sequester carbon is reduced for decades following the wildfire (Magnani et al. 2007 & Huybrechts et al. 2004). Each year wildfires add an estimated 3.5 x 10^{12} kg of carbon emissions to the atmosphere, representing approximately 40% of fossil fuel carbon emissions (Running 2006).

To mitigate the severity of fires and the corresponding increase in carbon flux, forest managers can utilize a variety of fuel treatments including tree harvesting, fuel mastication, and prescribed burning. Fuel treatments can include the creation of fuel breaks and/or complete slashing of trees (Agee et al. 2000), prescribed burning of understory and surface fuels (the duff, live fuels, and dead woody fuels lying on the forest floor), the use of harvesting (thinning and chipping of trees up to a specific size class), and/or the removal of understory trees and branches to reduce ladder fuels (van Wagtendonk 1996, Agee and Skinner 2005). Thinning (Figure 1a) is a widely used fuel treatment intended to promote redistribution of the remaining stems as well as reduce the number of stems within the stand (Graham et al. 2004). Shelterwood treatments (Figure 1b) are also commonly applied to many forests across the United States. With shelterwood treatments, mature trees are left to provide protection for a new even-aged stand of trees (Donner 2005).

Accurately estimating forest biomass is crucial to quantifying carbon storage and fluxes. To quantify carbon flux from wildfires, satellite imagery, along with field data, can provide a more accurate assessment than satellite imagery alone (Fang et al. 2001). Hurteau and North (2009) modeled the amount of live and dead tree C stores and flux over a century, with and without wildfire, after fuel treatments. Their results demonstrate that treatments can be an effective means of reducing CO_2 emissions from wildfires. Field studies of actual wildfires are necessary to refine model estimates of carbon fluxes and the relative effectiveness of management scenarios.

The objective of this study was to determine what impact fuel treatments had on carbon flux during the Tripod Complex Fire. Ground-based measurements and satellite imagery were utilized to estimate pre- and post-wildfire carbon stores in the area and carbon dioxide emissions that occurred during the fire. Changes in carbon storage and carbon dioxide emissions were compared in treated and untreated portions of the burned landscape.

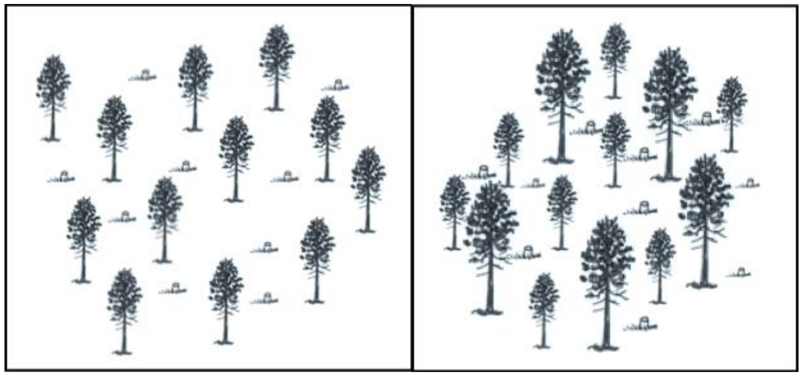

Figure 1. A) Shelterwood fuel treatment B) Thin fuel treatment

METHODOLOGY

Study Area

The study area was in the Tripod Complex Fire scar in Okanogan-Wenatchee National Forest, Washington (Figure 2). The Okanogan-Wenatchee National Forest is located in north-central Washington State bordered by Canada to the north, North Cascades National Park to the west, Lake Chelan to the south, and high desert to the east. The Forest alone encompasses over 1.6 million hectares. Annual precipitation varies widely, from more than 178 cm along the Cascade Crest to less than 25.4 cm at its eastern edge. Steep precipitation gradients greatly affect the diversity of forest and vegetation types across the area (USDA Forest Service 2009).

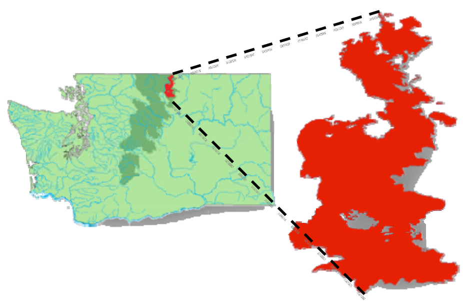

Figure 2. The Tripod Complex fire scar within the Okanogan-Wenatchee National Forest, Washington.

The Tripod Complex fire began as a series of lightning strikes in July, 2006. The fires were characterized by extreme fire weather and behavior and burned through dense forests with substantial mortality from mountain pine beetle. Approximately 70,800 hectares were burned by November 2006 when the fires were completely extinguished by winter storms. The fire burned the north eastern portion of the Forest and ranged from low elevation forests dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) to high elevation lodgepole pine (*P. contorta*) forests. A variety of past treatment areas with records dating back to the 1970s were burned in the wildfires.

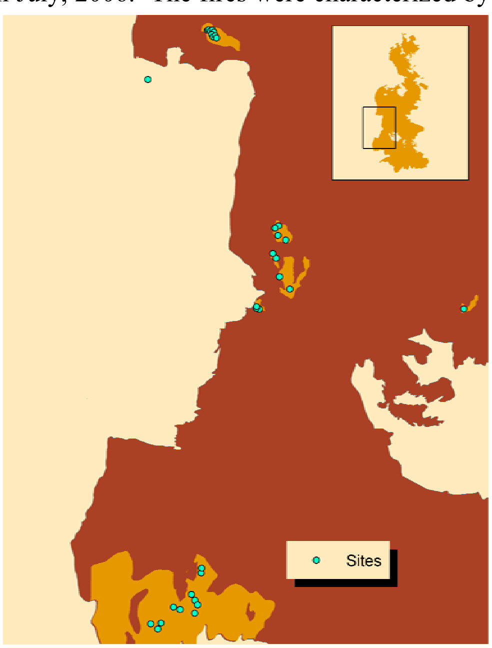

Figure 3. Plots sampled, June 22nd and 26th, 2009 in the Tripod Complex fire area.

Fieldwork

Fieldwork plots were selected based on the following criteria: treatments included thinned units and shelterwood units; plots were located on slopes less than 35 percent, within 400 m of a road, and at least 30 m within the edge of a given treatment unit. Two hundred points were randomly generated, split evenly between thin and shelterwood treatment types. Once in the field, plots were further selected based on road closures, travel time, and other concerns. As a result, a few plots were located using a random start point once the desired treatment area was reached. A total of 35 plots were sampled between June 22nd and 26th, 2009 (Figure

3).

For each of these plots, allometric data were gathered based on carbon storage categories: live and dead standing trees, stumps, live shrub and herbaceous cover, downed woody materials, and litter. Each sample plot (Figure 4) consisted of two circular plots, micro and macro, with radii of 7.5-m and 17-m respectively, were based around the plot-center. The macro plot is roughly the same size as a 30-m Landsat pixel. Additionally, three 20.12-m transects radiated 120˚ apart out from the central point.

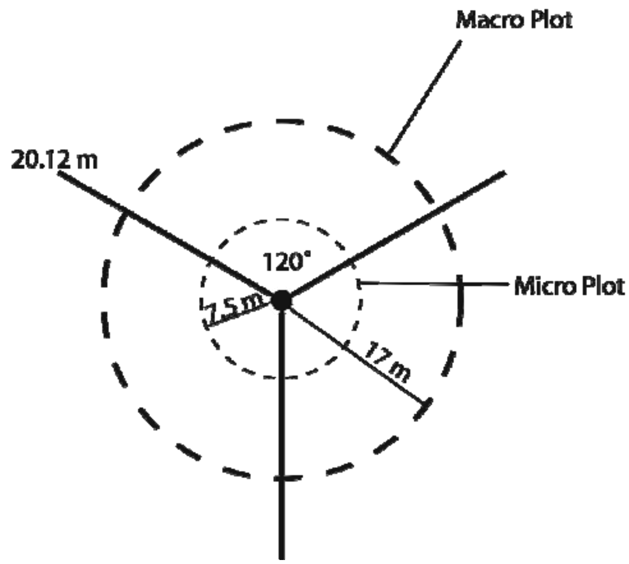

Figure 4. Plot diagram for field measurements, including 2 circular plots: macro 17-m radius and micro 7.5-m radius, and three 20.12-m transect lines.

Diameter at breast height (dbh), tree height, and height of the lowest contiguous branch were gathered for all live trees and any dead trees with a lean less than 45˚ inside the macro plot. Decay class of dead trees was recorded in five classes: 1) recently deceased, bark still firmly attached; 2) bark beginning to peel, but still solid; 3) no more bark, but relatively robust; 4) beginning to crumble, decomposition obvious; 5) very soft, soil-like, was recorded. If there were more than 30 trees in the macro plot (radius 17-m), then data were only sampled within the microplot. Additionally, diameter, height, and decay class were sampled for all stumps within the micro plot. Along the transects, line intercept cover was calculated to 15.2 cm for ground cover and categorized by grass, forb, shrub, coniferous litter, grass and shrub litter, and bare soil. Downed woody fuel pieces were tallied according to size category using the Brown (1974) planar intercept method: less than 0.6 cm in diameter (1 hour fuels) along the last 1.8 m of the transect, 0.6 - 2.5 cm in diameter (10 hour fuels) along the last 3.05 m of the transect, 2.5 - 7.6 cm in diameter (100 hour fuels) along the entire length of the transect. For pieces > 7.6 cm (1000 hour fuels) the diameter, decay class, and species, if obtainable, were recorded for every piece that intersected the transect. Litter depth was measured and categorized: conifer, grass, shrub, or wood rot, every 1.5 m along the transect.

Biomass Calculations

Biomass for the trees in each of the plots was calculated using an allometric equation. Jenkins et al. (2003) developed a generalized formula for tree species groupings. Equation 1 calculates biomass (kg) from dbh, when dbh ≥ 2.5 cm, and two species-specific parameters (Table 1).

(1) $\text{Biomass}_{tree} = \text{Exp}(ß_o + ß_1 * \ln(\text{dbh (cm)}))$

Equation 2 (Riccardi et al. 2007) was used to estimate stump biomass (kg) based on height, diameter, decay class, and particle density (PD) (Table 2):

(2) $\text{Biomass}_{stump} = \text{Diameter(m)}^2 * 0.25 * \Pi * \text{Height(m)} * \text{PD}$

The biomass of downed woody fuels (kg m^{-2}) was calculated following the procedure described by the *Handbook for Inventorying Downed Woody Material* (Brown 1974).

Allometric equations were utilized to estimate biomass for ground cover data. Due to limited time in the field, species-specific ground-cover data were not obtained. Instead, ground-cover data were grouped into categories: grass, shrub, forb, litter, and bare soil. Percent cover and height measurement were obtained for each living vegetation type. Lacking species-specific data, mixed-species equations were selected to represent each category. While slightly less

Table 1. Species group coefficients used in the calculation of tree biomass from Jenkins et al. (2003)

Parameters			
	Species Group	$ß_o$	$ß_1$
Hardwood	Aspen/alder/ cottonwood/ willow	-2.2094	2.3867
Softwood	Cedar/larch	-2.0336	2.2592
	Douglas-fir	-2.2304	2.4435
	Pine	-2.5356	2.4349
	Spruce	-2.0773	2.3323

accurate, these mixed-species equations were determined to be suitable as they had an r^2 value of 0.85, and were developed in central Washington (Olson and Martin 1981). Shrub biomass, and forb and grass biomass were estimated (kg m^{-2}) using equations 3, 4 and 5 respectively, where x_1 is percent cover, and x_2 is height (cm) (Gebert et al. 2008).

(3) $$\text{Biomass}_{\text{shrub}} = \frac{-0.62689+(0.05778 * x_1 * x_2)}{500}$$

(4) $$\text{Biomass}_{\text{forb}} = 13.66\text{x}10^{-4} * x_1$$

(5) $$\text{Biomass}_{\text{grass}} = 8.17\text{x}10^{-4} * x_1$$

Average litter biomass (kg m^{-2}) for each plot was calculated from Equation 6 (Brown and See 1981). Given that the compactness of litter was not taken into account when litter was measured, an average bulk density value of 22.1 (kg m^{-3}), between fluffy and normal, was used. Litter depths were averaged for each plot.

Table 2. Particle Density by tree species from Riccardi et al. (2007)

Tree species	Particle density (kg/m³)
Populus balsamifera ssp. trichocarpa	365.2
Pseudotsuga menziesii	493.4
Picea engelmannii	370
Abies grandis	414.9
Pinus contorta	459.7
Abies amabilis	482.1
Pinus ponderosa	448.5
Populus tremuloides	426.1
Abies lasiocarpa	358.8
Larix occidentalis	581.5
Unknown or decay class >3	299.5

(6) $$\text{Biomass}_{\text{Litter}} = \text{Bulk Density}_{(\text{kg/m}^3)} * \text{Depth}_{(\text{m})}$$

The totals for all of the previously stated biomass calculations were summed and then halved to get estimated carbon totals (Prichard et al. 2000). Soil carbon values for each plot were obtained from NASA's CASA CQUEST viewer, http://geo.arc.nasa.gov/sge/casa/cquestwebsite/index.html. Soil carbon values are derived from a model that outputs carbon sequestration data derived from satellite remote sensing at 8-km resolution (CQUEST Overview 2009). These data were then added to the carbon totals for each plot. The plot biomass totals were broken out into three categories, the biomass of the entire plot, all trees in the plot, and all living trees in the plot.

Satellite Imagery

Two Landsat 30-m spatial resolution scenes from July 1, 2006 and July 1, 2009 were acquired. Satellite imagery from 3.5 years after the fire was chosen to present as little temporal mismatch with fieldwork as possible. Additionally it allowed for the detection of re-growth of shrubs and grasses to be detected in the vegetation indices. The raw satellite data in each scene (except thermal and panchromatic bands) were converted to reflectance using an exoatmospheric model (Williams 1998) prior to the calculation of vegetation indices. In this study reflectance of six bands (blue, green, red, near infrared or NIR, and two mid-infrared or MIR) were used in the calculation of vegetation indices applied to the Landsat imagery. Five vegetation indices calculated from these scenes were used as independent variables (Figure 5).

Normalized differenced vegetation index, NDVI, by Rouse et al. (1973), is one of the most used indexes for biomass estimation (Equation 7). Corrected NDVI, by Nemani et al. (1993), incorporates the middle-infrared band into NDVI and produces stronger relationships between NDVI and biomass for forests (Equation 8). Enhanced Vegetation Index (EVI), by Huete et al. (2002), where L=1, C_1 = 6, C_2 = 7.5, and G (gain factor) = 2.5, aims to improve the detection of vegetation in high biomass regions (Equation 9). The Greenness Ratio, by Peterson (2008), represents a greenness of annual grass infestation visible in false color maps (Equation 10). The GPP algorithm, by Xiao et al. (2004), produces gross primary productivity estimates in g C m^{-2} (Equation 11), by incorporating light-use efficiency in g C MJ^{-1} PAR (LUEg), Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), and Photosynthetically Active Radiation (PAR). These variables provide the initial calculation for carbon cycle analysis. Values corresponding to the coordinates for each of the field plots were extracted and applied to a linear regression with the biomass values.

(7) $$\text{NDVI} = \frac{NIR - \text{Red}}{NIR + \text{Red}}$$

(8) $$\text{NDVIc} = NDVI\left[1 - \frac{mIR - mIR_{\min}}{mIR_{\max} - mIR_{\min}}\right]$$

(9) $$\text{EVI} = G\frac{P_{NIR} - P_{\mathrm{Re}\,d}}{P_{NID} - C_1 P_{\mathrm{Re}\,d} - C_2 P_{Blue} + L}$$

(10) $$\text{GreennessRatio} = \frac{Band4}{0.5(Band2 + Band7)}$$

(11) GPP = LUEg (FAPAR * PAR)

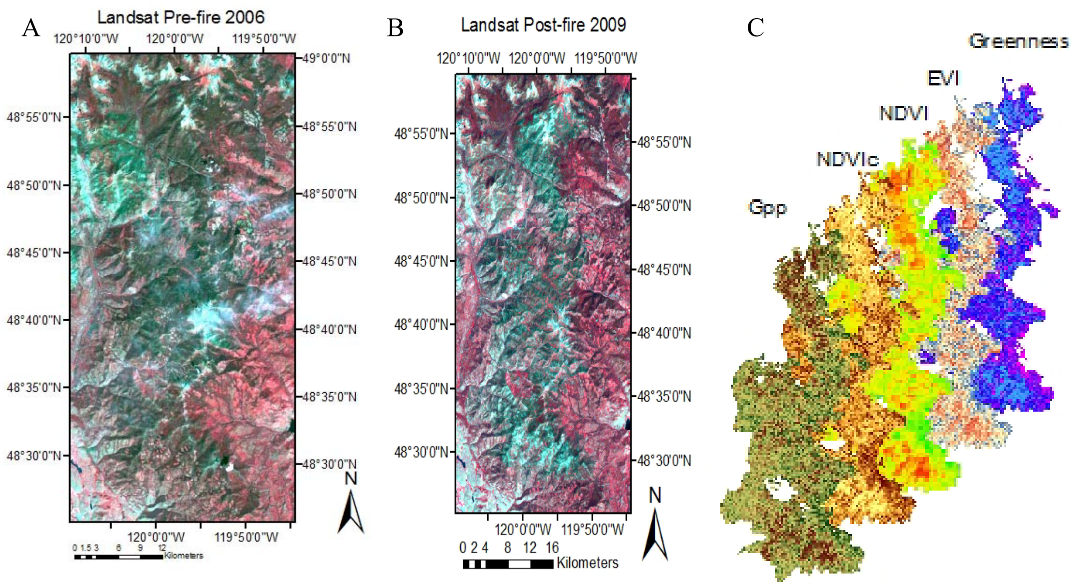

Figure 5. A) Pre-fire Landsat scene from July 1, 2006 B) Post-fire Landsat scene from July 1, 2009, both A and B shown with bands 4, 3, 2. C) The five vegetation indices: GPP, NDVIc, NDVI, EVI, and Greenness Ratio.

Moderate Resolution Imaging Spectroradiometer (MODIS) sensor collects spectral information in similar portions of the electromagnetic spectrum as Landsat. MODIS collects information from 36 spectral bands ranging in wavelength from 0.4 µm to 14.4 µm. MODIS has the potential to record long-term fire effects and has a high temporal resolution covering the same spot every day. When compared to Landsat MODIS has a high temporal resolution, its spatial resolution is coarse. GPP from MOD17A2 is an 8-day composite and has a resolution of 1 km, while NDVI and EVI from MOD13Q1 are 16-day composites with a resolution of 250 m (Figure 6). Pre-fire scenes were obtained for July 12, 2006 and post fire scenes were obtained for June 10, 2009. Values from post fire NDVI, EVI and GPP, were correlated with the biomass totals using a linear regression.

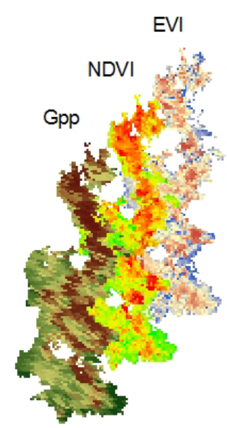

Figure 6. GPP, NDVI and EVI obtained from MODIS.

A ΔNDVI model was used to demonstrate the loss of healthy vegetation, which sequesters carbon, due to the Tripod Complex fire. The pre and post-fire NDVI images from Landsat and MODIS were temporally differenced using the ΔNDVI algorithm (Equation 12). A similar process was applied (Equation 13) to pre and post-fire GPP images to detect the change in carbon sequestration that occurred.

(12) $$\Delta\text{NDVI} = \text{NDVI}_{\text{Pre}} - \text{NDVI}_{\text{Post}}$$

(13) $\Delta GPP = GPP_{Pre} - GPP_{Post}$

Carbon Dioxide Emissions

Carbon dioxide emissions were calculated two different ways. Emissions for the entire fire as well as emissions per treatment area were determined according to burn severity information from Newcomer et al. (2009) and Key and Bensen (1999). To calculate CO_2 emissions, the following equation was used (Wiedinmyer et al. 2006):

(14) $E_i = A*B*CE*e_i$

Where:

A= treatment area (m^2)
B = fuel loading, or pre-fire biomass value ($Mg\ m^{-2}$)
CE = combustion efficiency (%)
e_i = emission factor (kg per Mg)

Calculations included fuel bed classifications from the Fuel Characteristics Classification System (FCCS) developed by Fire and Environmental Research Applications. The FCCS fuel beds were applied to Landsat pixels using a crosswalk between the 1998 Vegetation classification and FCCS fuelbeds (McKenzie et al. 2007). Fuelbeds for four burn severity classifications, assigned by Newcomer et al. (2009), were extracted from a fuelbed layer for the Okanogan-Wenatchee National forest. Area values (A) were then calculated for each fuelbed-burn severity classification area. Next, biomass amounts (B) corresponding to specific fuelbed types were obtained for six different biomass categories (canopy, shrubs, non-woody fuels, litter/lichen/moss, and ground fuel) from FCCS data. Combustion efficiencies (CE) for each biomass category were estimated for each burn severity according to the CBI (composite burn index) datasheet (Key and Bensen 1999) (Table 3) and the burn severity classification assessment.

Table 3. Percentage of fuels consumed by fuelbed category (FCCS) and burn severity classification (Newcomer et al., 2009) based on the composite burn index (Key and Bensen 1999)

	Burn Severity Classification			
	High	**Mid**	**Low**	**Unburned**
Canopy	100%	55%	12.5%	0%
Shrubs	100%	75%	25%	0%
Nonwoody Fuel	97.5%	80%	30%	0%
Woody Fuel	50%	32.5%	15%	0%
Litter/Lichen/Moss	100%	100%	50%	0%
Ground Fuel	100%	50%	10%	0%

An emissions factor (e_i) of 1569 was used (Wiedinmyer et al. 2006). Emissions were calculated for each fuelbed value in a specific burn severity. Finally, these emissions were summed, either for each treatment area, or for the entire fire.

RESULTS AND DISCUSSION

Biomass totals for each plot ranged from 0.79 kg m^{-2} for a plot with only saplings to 21.43 kg m^{-2} for a plot with 13 large trees. The biomass of the entire plot, all trees in the plot, and all living trees in the plot were correlated to Landsat and MODIS NDVI, EVI, GPP, and Landsat NDVIC and Greenness Ratio. The field data showed poor to modest correlations with the satellite imagery (Table 4).

Table 4. Correlation values (r^2) for MODIS and Landsat indices against biomass totals

	MODIS			**Landsat**				
	NDVI	**EVI**	**GPP**	**NDVI**	**EVI**	**GPP**	**NDVIC**	**Greenness**
Total Plot	0.0636	0.006	0.010	0.401	0.145	0.366	0.373	0.425
Tree biomass	0.109	0.171	0.072	0.361	0.042	0.329	0.434	0.404
Live tree biomass	0.184	0.128	0.080	0.362	0.086	0.330	0.347	0.440

For MODIS, the low correlations (0.006 to 0.184) are most likely due to the difference between pixel size and treatment area size. The MODIS indices were averaged for pixel sizes ranging from 250 m^2 to 1 km^2. This is larger than many of the treatment areas, allowing the MODIS values to cover both treated and untreated areas. As a result, MODIS imagery is not a viable tool for estimating carbon storage in the treatment areas examined in this study.

The moderate correlations, with a maximum r^2 of 0.401 for total plot and 0.434 for tree biomass are most likely explained by the presence of dead debris in the plot. Vegetation indices are based on reflectance in the infrared region of living vegetation. The field plots had various degrees of burn severity, ranging from high, with > 90% non-green biomass, to unburned, with < 2% non-green biomass. Non-green biomass was calculated in field measurements, but not detected in the vegetation indices, skewing the data points in many directions and hampering the correlations. However there was not a strong improvement in the correlation values when dead vegetation was removed: live tree biomass.

Overall pre-fire GPP was 4.4×10^7 kg per day and post-fire GPP was reduced to 1.6×10^7 kg per day (Figure 7). Both ΔNDVI and ΔGPP showed less change in treatment areas than the entire fire. For example, the average change in GPP was -0.199 kg C m^{-2} for the treatment areas whereas the average change for the entire fire was -0.320 kg C m^{-2}.

The emissions for the total fire were 7.1×10^9 kg of CO_2. Treated areas emitted an average of 2.79 kg CO_2 m^{-2}, compared to 10.08 kg CO_2 m^{-2} emitted by the total fire (Figure 8).

Table 5. Differences between treated and untreated areas of the fire for ΔGPP and CO_2 Emissions

	ΔGPP kg C m^{-2} per day	**CO_2 Emissions** kg m^{-2}
Treated Areas	-0.199	2.79
Total Fire Area	-0.320	10.08

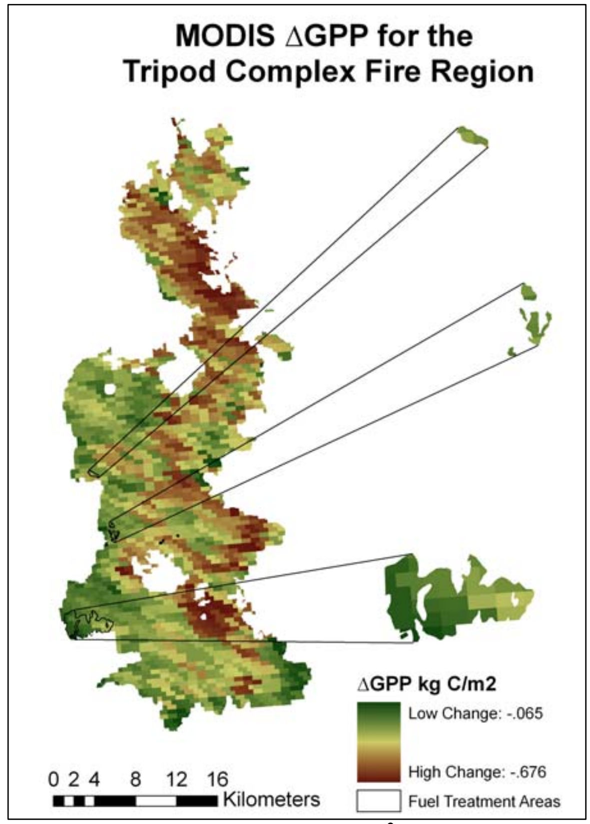

Figure 7. Map of ΔGPP in kg C m^{-2} from MODIS GPP for the entire fire and by treatment area.

Fuel treatments, while effective in reducing carbon flux during a wildfire, are not appropriate for all forest types. Low elevation forest types such as ponderosa pine forests of the Okanogan National Forest historically had high frequency, low severity fires. Treatments to reduce fuels and mitigate fire severity can be successful in these forest types (Agee and Skinner 2005). However, the majority of the Tripod fire area is within high elevation forest types and roadless areas. Fuel treatments are unlikely to be effective in high elevation forests such as the lodgepole pine and Engelmann spruce forests (Agee and Skinner 2005) that burned in the Tripod fires. These forests are associated with an infrequent, high severity fire regime and are also generally located in roadless and ecologically sensitive areas.

If a quarter of the burned region had been treated, approximately 4.91×10^8 kg of CO_2 would not have been emitted during the fire. Additionally the fire region would be sequestering an additional 6.5×10^8 kg of carbon per year. While the treatment areas studied succeeded in reducing carbon emissions, there was insufficient sample size to make a statistically significant claim regarding which specific treatment type is most effective.

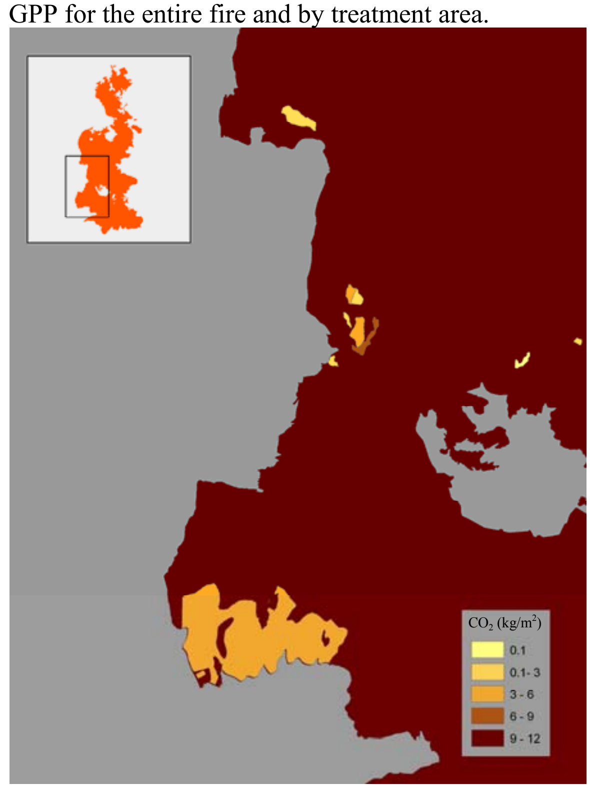

Figure 8. Map of treated areas and the fire scar, classified by CO_2 emissions amount in kg m^{-2}.

CONCLUSION

Carbon dioxide emissions and sequestration results indicate that fuel treatments reduced the change in carbon flux during the Tripod Complex fire. Emissions from the fire were 72% lower in treated areas and sequestration rates after the fire were 38% higher. In order to make a statistically significant determination of the effectiveness of unique fuel treatments, more field measurements need to be obtained. A wider range of treatment areas need to be sampled, with more plots within each specific treatment area.

Finding significant differences in carbon flux between treatment types would allow forest managers to make more effective decisions regarding forest carbon management. The creation of a fuel treatment applicability map showing areas where fuel treatments could be effectively applied would further help forest managers by minimizing costs and maximizing treatment effectiveness. Such a map would also help estimate the impact of the treatments on carbon flux with greater accuracy.

Variation in pixel sizes among satellites affected the correlations with ground biomass measurements. The 17-meter plots, and even many of the treatment areas, were too small to be represented by the size of MODIS pixels. Landsat pixels, on the other hand, were better suited for this level of ecosystem evaluation as they are far closer to the actual plot size. Additionally, satellites were not effective at measuring non-green biomass (i.e. dead and decaying material), thereby ignoring a portion of a plot's total biomass. Investigations into new algorithms that can detect non-green biomass more effectively could lead to better approximations of biomass and help reduce field crews.

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