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Effects of fuel treatments on carbon-disturbance relationships in forests of the northern Rocky Mountains☆

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ABSTRACT

Fuel treatments alter conditions in forested stands at the time of the treatment and subsequently. Fuel treatments reduce on-site carbon and also change the fire potential and expected outcome of future wildfires, including their carbon emissions. We simulated effects of fuel treatments on 140 stands representing seven major habitat type groups of the northern Rocky Mountains using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Changes in forest carbon due to mechanical fuel treatment (thinning from below to reduce ladder fuels) and prescribed fire were explored, as well as changes in expected fire behavior and effects of subsequent wildfire. Results indicated that fuel treatments decreased fire severity and crown fire occurrence and reduced subsequent wildfire emissions, but did not increase post-wildfire carbon stored on-site. Conversely, untreated stands had greater wildfire emissions but stored more carbon.

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1. Introduction

The extent to which fire and fuel management practices can protect forest carbon stores, and the short and long term trade-offs of these practices are important issues for forest managers and policy makers. Forest vegetation can serve as a carbon reservoir and thus has the potential to mitigate climate change (Denman et al., 2007). Carbon is stored in forests in the form of woody and leafy plant material, soil microbes, and litter and duff on the forest floor. When forests burn, some of this stored carbon is released into the atmosphere in the form of smoke emissions (Wiedinmyer and Neff, 2007) and through subsequent decomposition of residual fire-killed biomass (Harmon and Marks, 2002). Managing forests for climate change mitigation requires an assessment of the potential short and long term effects of land management decisions not only on carbon stocks, but also on fire risk and on ecosystem benefits such as biodiversity and services such as water.

Fuel treatments are common forest management practices used to reduce the intensity and severity of subsequent wildfire (Agee and Skinner, 2005; Fiedler et al., 2004; Graham et al., 1999, 2004; Peterson et al., 2005; Reinhardt and Ryan, 1998). Fuel treatments may include thinning, burning, and mastication, alone or in combination. Fuel treatments can affect forest carbon storage directly and indirectly. In the short-run, fuel treatments such as thinning or prescribed fire directly remove carbon from a stand. Subsequent carbon dynamics are also affected. Tree harvest (commercial thinning) removes some material from the site and also typically converts some biomass from standing live to dead surface material (for example unmerchantable crown material), although some harvest treatments may remove most of the harvested material from the site. Prescribed fire removes some fuel from the stand in the form of emissions, and also coverts some biomass from standing live trees to standing dead trees due to fire-caused mortality. These dead trees fall to the forest floor over time, causing accumulations of fuels on the forest floor. Removal of dead and live biomass from forested stands can thus influence the extent to which a subsequent unplanned wildfire or a planned prescribed burn reduces stand carbon stores. To evaluate the effects of fuel treatment on carbon, it is necessary to consider not only the direct effects of fuel treatments on carbon stores, but also the effectiveness of the fuel treatment in limiting subsequent carbon losses from wildfire (Finkral and Evans, 2008).

Fuel treatments of any kind can be expected to alter the subsequent development of the stand and thus the carbon sequestration rate. Growth of individual trees can be increased due to greater nutrient availability following prescribed fire and reduced moisture and light competition following thinning or prescribed fire. Effects on stand net productivity depend on the specifics of the treatment.

This paper reports the simulated effects of fuel treatments on stand-level carbon dynamics and fire characteristics in the northern Rocky Mountains, USA. We simulated the effects of fuel treatments on forest carbon in 140 stands that represent seven

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major habitat type groups of the northern Rocky Mountains. The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) was used to simulate effects on forest carbon of mechanical fuel treatment (thinning from below to reduce ladder fuels), prescribed fire and wildfire. We modeled direct effects of fuel treatments on carbon stocks. We simulated wildfire 5 years after the fuel treatments and assessed the effectiveness of the fuel treatments on ameliorating wildfire severity. We report on the effects of fuel treatment on wildfire emissions, and also on carbon recovery rates following wildfire.

2. Methods

We evaluated direct treatment effects on carbon at the stand level by computing the amount of carbon removed in typical thinning and prescribed burn treatments. We then simulated wildfire and evaluated the effects of the treatments on fire behavior and carbon emissions at the time of the wildfire and subsequent carbon dynamics over a 95-year simulation period. These responses were computed using the carbon output (Hoover and Rebain, 2008) of the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston, 2003).

In this study we confined our analysis and discussion to fire behavior and effects at the stand-level and did not evaluate landscape-level impacts of treatments. We used data from 140 stands in seven habitat type groups found in northern Idaho and western Montana.

2.1. FFE-FVS

The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) is a nationally supported tool available to forest managers and is calibrated for most of the United States. It is a stand-level model that simulates fuel dynamics and potential fire behavior over time in the context of stand development and management. FFE-FVS links existing models to represent forest stand development (the Forest Vegetation Simulator (FVS), Wykoff et al., 1982), fire behavior (Rothermel, 1972; Van Wagner, 1977; Scott and Reinhardt, 2001), and fire effects (Reinhardt et al., 1997). Users can simulate fuel treatments including prescribed fire, wildfire, thinning, and mechanical treatments. Model output includes stand descriptors and predicted fuel loadings over time. If a prescribed fire or wildfire is simulated, output also includes predicted fire behavior, fuel consumption, smoke production, and tree mortality.

FVS is an individual tree, distance-independent growth and yield simulator. It models tree growth, tree mortality, and regeneration using empirical relationships. It is accepted for growth and yield modeling by the Chicago Climate Exchange (CCX), and California Climate Action Registry. The Fire and Fuels Extension simulates fuel accumulation on an annual time step from stand dynamics (including litterfall and snagfall) and management (including activity fuels from harvest treatments), and removal of fuel through decay, mechanical treatment, prescribed fire, and wildfire. Annual decay rates were based on literature review and varied from 0.5 for litter to 0.002 for duff. For woody fuels annual decay rates varied with diameter of the woody material. In the event of fire, Rothermel's (1972) fire behavior model is used to model fire intensity. Crown fire behavior is predicted using the algorithm of Scott and Reinhardt (2001). Tree mortality, fuel consumption, and smoke production are modeled using methods from FOFEM (Reinhardt et al., 1997). The snag and fuel dynamics algorithms contained in FFE-FVS are geographically specific and were developed from literature review (Reinhardt and Crookston, 2003). Fuels and stand characteristics drive the predictions of fire behavior, which in turn drive predictions of fire effects including tree mortality, fuel consumption and carbon emissions. Tree mortality and fuel consumption in turn drive subsequent fuel dynamics.

FFE-FVS reports carbon in standing live, standing dead, roots, surface fuel, including litter and duff, harvest and emissions (Hoover and Rebain, 2008). Although soils can store a significant portion of the carbon in a forested site (Johnson and Curtis, 2001), FFE-FVS does not currently model soil carbon. In addition to the carbon stored in the stand, some of the carbon removed by thinning may be stored in durable wood products. This contrasts with the carbon removed by prescribed fire and wildfire, which goes directly into the atmosphere. FFE-FVS models persistence of carbon from harvested material in landfills and long-lasting wood products, based on diameter, species and geographic region. FFE-FVS is well suited for evaluating effects of fuel treatments and fire on carbon because it simulates stand dynamics, fuel dynamics, fire behavior, and fire effects explicitly. The model is initialized using stand data in the form of tree characteristics such as species, size and condition, as well as surface fuel quantities if available. Carbon is calculated directly from the stand data, fuel pools, harvested trees and fire emissions. Fig. 1 shows an example of FFE-FVS output illustrating carbon dynamics following wildfire, with and without fuel treatment.

2.2. Modeling inputs

We used data from the Forest Inventory and Analysis (FIA) database (http://fia.fs.fed.us). We selected stands from seven

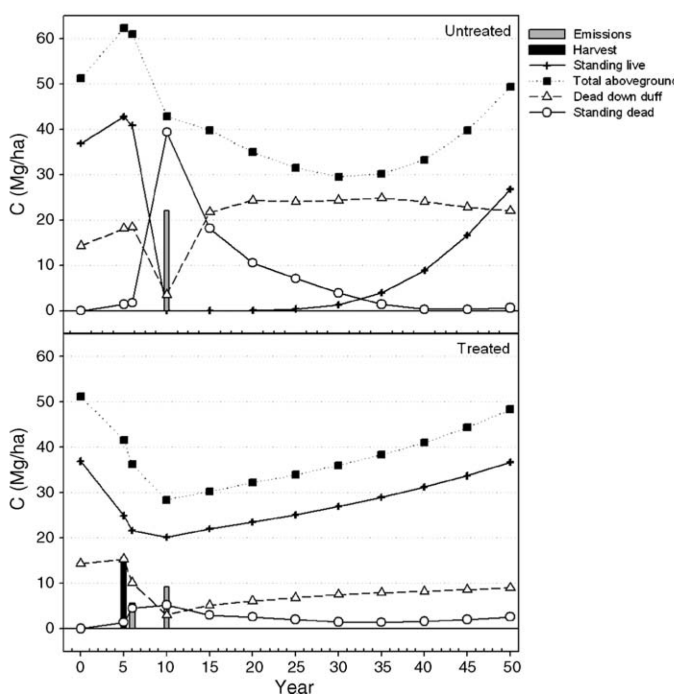

Fig. 1. Treatment and fire shift carbon from one pool to another. This figure shows carbon pools in a ponderosa pine stand. At the beginning and end of the 50-year simulation, the treated and untreated stands have similar amounts of total above ground carbon (around 50 Mg/ha). The treatment in 2002/2003 removed 15.7 Mg/ha of carbon in harvested material and 5.6 in emissions. Both stands are burned by wildfire under similar conditions in 2007. The treated stand lost an additional 9.2 Mg/ha of carbon in wildfire emissions, while the untreated stand lost 22.1 Mg/ha. The wildfire in 2007 burned as a stand replacement crown fire in the untreated stand and as a surface fire with minimal tree mortality in the treated stand, largely because the treatment removed a large number of small trees that served as ladder fuels in the untreated stand. The wildfire in the untreated stand converted the standing live trees to standing dead. Over time as dead trees fell that pool declined and the surface dead and down pool increased.

habitat type groups: subalpine fir (*Abies lasiocarpa*) and mountain and western hemlock (*Tsuga mertensiana, Tsuga heterophylla*) (NI5); western hemlock and western redcedar (*Thuja plicata*) (NI8); ponderosa pine (*Pinus ponderosa*), occasional Douglas-fir (*Pseudotsuga menziesii*), and Rocky Mountain juniper (*Juniperous scopulorum*) (MT2); Douglas-fir (MT6), lodgepole pine (*Pinus contorta*) (MT7); western larch (*Larix occidentalis*), western, white pine (*Pinus monticola*), Douglas-fir, lodgepole pine and spruce (MT9); and subalpine fir, spruce, whitebark pine and subalpine larch (MT10) (Table 1) defined based on their fire ecology (Bollenbacher, 2009; Fischer and Bradley, 1987; Smith and Fischer, 1997). The FIA program has collected stand-level data across the nation using a set of nested plots located along a 5-km grid. Sample size varied from 11 to 27 stands because some habitat type groups had few samples that met our criteria. We restricted stands to those that supported a tree density sufficient to make thinning treatment feasible. Minimum basal area by habitat type group (Table 1) was used for this determination. Thus, we excluded stands that already met target densities without treatment. We also restricted plot selections to mature but not ancient stands (age greater than 80 and less than 200 years). For the Montana habitat type groups, we used FIA data that included sampled duff and woody debris loads. These data were not available for the northern Idaho types, so we used default duff and woody fuel values provided by FFE-FVS to initialize our runs.

2.3. Simulation and analysis

The set of fuel treatments simulated in this study represent common stand-level treatments used in forest and ecosystem

Table 1
Habitat type groups used in this study.

Habitat type GroupType	Overstory vegetation	Fire intervals and fuels	Mechanical fuel treatment	Alternate treatment
NI5: Moist, lower subalpine habitat types (Smith and Fischer, 1997)	Subalpine fir (*Abies lasiocarpa*) and mountain and western hemlock (*Tsuga mertensiana, Tsuga heterophylla*) in climax stands; Engelmann spruce (*Picea engelmannii*) and lodgepole pine (*Pinus contorta*) dominate cooler sites in seral stages; other seral species include Douglas-fir (*Pseudotsuga menziesii*), western white pine (*Pinus monticola*) and western larch (*Larix occidentalis*)	Mixed severity 27–150 years Stand replacement 174 years Fuels can be heavy and live fuels continuous. Typically fuels dry slowly and moisture limits fire intensity and spread. In dry seasons however, crown fires may initiate, and even surface fires may be lethal to overstory trees.	Thin from below to a residual basal area of 23 m^2/ha (100 ft^2/acre). Burn unmerchantable trees and branchwood in piles.	None
NI8: Moderate and moist western hemlock and western redcedar habitat types (Smith and Fischer, 1997)	Climax species include western hemlock and western redcedar (*Thuja plicata*); seral species include western white pine, western larch, Douglas-fir, subalpine fir, Engelmann spruce, grand fir (*Abies grandis*), ponderosa pine (*Pinus ponderosa*) and lodgepole pine.	Mixed severity 42–186 years Stand replacement 200+ years Productive sites and heavy fuels. This group is diverse in vegetation and successional patterns.	Thin from below to a residual basal area of 25 m^2/ha (110 ft^2/acre). Burn unmerchantable trees and branchwood in piles.	None
MT2: warm dry ponderosa pine habitat types (Fischer and Bradley, 1987)	Ponderosa pine; occasional Douglas-fir, Rocky Mountain juniper (*Juniperous scopulorum*)	Non-lethal 5–25 years Fuels are typically light and dominated by grass.	Thin from below to a residual basal area of 14 m^2/ha (60 ft^2/acre). Broadcast prescribed burn the year following the thinning; burn unmerchantable trees and branchwood in piles.	Broadcast underburn only
MT6: moist Douglas-fir habitat types (Fischer and Bradley, 1987)	Douglas-fir is climax and may also dominate seral stands. Other seral species include ponderosa pine, lodgepole pine, whitebark pine (*Pinus albicaulis*) and western larch.	Non-lethal 15–24 years, infrequent stand replacement fire. Fuels are variable.	Thin from below to a residual basal area of 16 m^2/ha (70 ft^2/acre). Broadcast prescribed burn the year following the thinning; burn unmerchantable trees and branchwood in piles.	Broadcast underburn only
MT7: cool habitat types usually dominated by lodgepole pine (Fischer and Bradley, 1987)	Lodgepole pine, may include some Douglas-fir, spruce, subalpine fir and whitebark pine	Lethal fire 100+ years; in some cases with mixed or non-lethal fires at shorter intervals. Fuels are variable and may be heavy. They are often dominated by large woody material.	Thin from below to a residual basal area of 18 m^2/ha (80 ft^2/acre). Burn unmerchantable trees and branchwood in piles.	None
MT9: moist, lower subalpine habitat types (Fischer and Bradley, 1987)	Overstory species include western larch, western white pine, Douglas-fir, lodgepole pine and spruce. A dense understory of subalpine fir, spruce and mountain hemlock develops in the absence of disturbance.	Non-lethal 30 years; stand replacement 100+ years. Climax stands rarely occur. High loadings of both live and dead fuels are typical.	Thin from below to a residual basal area of 18 m^2/ha (80 ft^2/acre). Broadcast prescribed burn the year following the thinning; burn unmerchantable trees and branchwood in piles.	Broadcast underburn only
MT10: cold, moist upper subalpine habitat types (Fischer and Bradley, 1987)	Subalpine fir, spruce, whitebark pine and subalpine larch.	Fires are infrequent and can have long term effects.	None	Broadcast underburn only

Table 2
Simulated conditions for prescribed fires and wildfires.

Environmental condition	Prescribed fire	Wildfire
6 m windspeed, km/h	13	32
Temperature, °C	21	21
Moisture content of dead fuels <2.54 cm in diameter, %	12	4
Moisture content of dead fuels 2.54–7.62 cm in diameter, %	14	5
Moisture content of dead fuels 7.62+ cm in diameter, %	25	10
Moisture content of duff, %	125	15
Moisture content of live fuels, %	70	70

management in the Forest Service Northern Region (Table 1). Fuel treatment prescription parameters were provided by the Forest Service Regional Silviculturist (Bollenbacher, 2009). Thinnings were simulated 5 years after the start of the simulation period. Thinnings were from below to a residual basal area that was dependent on forest type (Table 1). These thinnings served to remove ladder fuels, increase canopy base height, and decrease the likelihood of crown fire behavior. We simulated whole tree yarding to remove activity fuels from the site. We assumed that these activity fuels were completely consumed by burning. Prescribed underburns were simulated the year following thinning in forest types MT2, MT6 and MT9. In MT2, MT6, MT9 and MT10, we also simulated prescribed underburning without thinning as an alternative treatment. In the north Idaho habitat types (NI5, NI8), as well as the Montana lodgepole pine types (MT7) prescribed underburning was not simulated either in combination with thinning or as a stand-alone alternative treatment, since the tree species are so susceptible to fire injury that prescribed burning is not typically practiced. All prescribed fires were simulated under moderate burning conditions (Table 2).

Wildfires were modeled for both treated and untreated stands 10 years after the start of the simulations. Wildfire conditions were representative of dry, late summer wildfires that may be expected to result in crown fire behavior in stands with continuous fuels (Table 2). For fire behavior simulations, both wildfire and prescribed fire, we had FFE-FVS create a custom fire behavior fuel model for each stand based on the modeled fuel loadings and other fuel characteristics. Fuels, and, as a consequence, expected fire behavior and effects, varied within forest types depending on stand structure, composition, and density. Thus, for each stand, fire behavior was predicted explicitly and not simply assigned.

We simulated natural regeneration in the stands using default predictions generated by FFE-FVS. These predictions are sensitive to geographic area, habitat type, and stand density. Carbon persisting in harvested material was simulated by FFE-FVS over time, based on the diameter distribution and species of the harvested material.

We computed descriptive statistics to characterize the amount of carbon in the modeled stands at the time of inventory and the amount removed by the simulated thinning and prescribed fire treatments in each habitat type group. We also calculated a number of metrics to assess effects of treatment on subsequent disturbance. These include estimates of the potential fire impact should a fire burn through the stand under severe weather conditions 10 years after treatment. Fire response variables included flame length (m), tree mortality (% of stand basal area), fire type (surface, passive crown fire, conditional crown fire or active crown fire), carbon emissions at the time of wildfire (Mg/ha), subsequent carbon losses due to decomposition of fire-killed vegetation (Mg/ha), years after wildfire until the stand again became a carbon sink, and carbon at year 95 as a proportion of carbon at the beginning of the simulation. We tested to see whether treatment had a significant effect on these variables by comparing treated and untreated stands using independent samples t-tests, $p = 0.05$, for equality of means (2-tailed and equal variances assumed) to compare means. These statistics are provided to give a sense of the relative strength of the results, however, all treatment effects are simulated, not observed, so statistical significance is to some extent an artifact of model performance. The exception is that variability of initial conditions is a reflection of observed, not simulated variability.

3. Results

Total stand carbon, carbon in live and dead standing trees, surface woody fuel, litter and duff, and coarse roots are reported in Table 3. The largest values were found in the northern Idaho western hemlock and western red cedar habitat types (NI8), followed by the moist, lower subalpine habitat types of Idaho (NI5) and Montana (MT9). The smallest amounts of carbon were found in the dry, warm Montana habitat types (MT2).

The simulated treatments removed an average of about 20% of the pretreatment carbon from the stands in the form of harvested material (Table 4), with the smallest removals (10.6 Mg/ha) from the warm dry habitat types with the smallest pretreatment carbon stocks (MT2), and the largest removals (41.9 Mg/ha) from the moist western cedar/western hemlock types of northern Idaho (NI8). The post-thinning emissions (from prescribed underburning and pile burning of the yarded unmerchantable tops) removed an additional but smaller portion of stand carbon, on the order of 8–20% of pretreatment stand carbon.

Crown fire behavior was substantially reduced by prescribed fire and almost eliminated by mechanical fuel treatments (Table 5). Wildfire flame length was also reduced by treatments. Fire-caused tree mortality was reduced for all forest types, in some cases dramatically, because the thinning from below and prescribed fire selectively removed the smallest and most vulnerable trees.

Effects of wildfire on carbon stocks were substantial and lasting, for both treated and untreated stands (Fig. 2). In all forest types, more carbon was released at the time of wildfire from the untreated stands than the treated stands (Table 6). In most cases,

Table 3
Mean and standard deviation, carbon stored in standing live trees, standing dead trees, surface woody fuels and duff, and total carbon on-site, including belowground, tons/acre. These values are derived from the sample data, and reflect initial conditions before simulations.

Forest type	n	Carbon, Mg/ha, mean, std. dev					
		Standing live trees	Standing dead trees	Surface woody debris	Forest floor: litter and duff	Coarse roots, live and dead	Total
NI5	14	84.99 ± 48.02	0.43 ± 0.56	19.73 ± 4.92	17.73 ± 5.88	22.19 ± 11.22	145.95 ± 60.64
NI8	11	107.81 ± 45.36	0.34 ± 0.46	33.89 ± 22.38	23.16 ± 6.45	26.21 ± 10.14	191.84 ± 54.97
MT2	14	33.31 ± 27.68	0.82 ± 12.09	2.81 ± 12.92	10.27 ± 12.76	10.69 ± 6.14	58.35 ± 45.99
MT6	25	70.83 ± 26.44	5.49 ± 8.26	12.32 ± 11.41	13.45 ± 7.19	23.10 ± 8.45	125.92 ± 37.90
MT7	27	65.66 ± 26.55	9.12 ± 8.30	20.09 ± 16.46	12.97 ± 7.15	16.89 ± 5.79	125.28 ± 38.24
MT9	24	69.84 ± 27.68	10.22 ± 12.09	23.25 ± 12.92	22.62 ± 12.76	20.47 ± 6.14	147.05 ± 45.99
MT10	25	45.33 ± 13.40	6.37 ± 5.66	15.91 ± 12.04	12.21 ± 8.84	18.84 ± 5.86	99.49 ± 26.61

Table 4
Carbon removed by treatment, Mg/ha, mean, std. dev. Post-thinning emissions include emissions from broadcast burning in MT2, MT6, MT9 and MT10, and pile burning of activity fuels in all types except MT10.

Forest type	Thinning removals		Post-thinning emissions		Emissions from the prescribed burn only treatment	
	Mg/ha	% of initial	Mg/ha	% of initial	Mg/ha	% of initial
NI5	33.31 ± 34.84	18.71 ± 11.51	12.83 ±7.51	8.46 ± 2.92	n.a	n.a
NI8	41.90 ± 38.10	19.22 ± 13.07	16.41 ± 9.28	8.15 ± 2.85	n.a	n.a
MT2	10.64 ± 7.64	16.55 ± 9.31	12.65 ± 6.60	20.84 ± 8.51	6.79 ± 2.87	10.42 ± 3.36
MT6	35.98 ± 23.37	26.32 ± 13.00	15.97 ± 9.32	11.92 ± 5.27	13.11 ± 7.20	10.11 ± 4.82
MT7	31.15 ± 22.27	23.03 ± 12.47	17.37 ±10.36	13.53 ± 7.36	n.a.	n.a.
MT9	33.32 ± 23.46	20.97 ± 10.13	16.71 ± 9.24	11.15 ± 4.41	22.76 ± 9.18	14.58 ± 3.77
MT10	n.a.	n.a.	n.a.	n.a.	15.81 ± 6.59	14.98 ± 4.93

however, even these larger fire emissions still left the untreated sites with larger residual carbon stocks immediately post-fire (Fig. 3). In addition to immediate carbon losses from wildfire emissions, there was a subsequent decline in carbon following wildfire as fire-killed trees decomposed (Fig. 2, Table 6). Carbon loss to decomposition was partially offset by stand growth – the values reported in Table 6 show the *net* decline in carbon stocks after fire. The magnitude of this additional net loss was variable, but was less in treated than untreated stands. This is an expected result since some of smaller trees that would be killed by wildfire and then decompose were removed in the fuel treatments. Carbon stocks continued to decline for a variable length of time until growth exceeded decomposition and the site again became a net carbon sink. The exception to this general pattern occurred in treated stands in NI8, which began to show net increases in carbon immediately following wildfire. NI8 is also the forest type with highest pretreatment carbon levels, indicating its generally high productivity. The recovery time (time from fire until the site again became a carbon sink) was shorter on the treated than the untreated sites. Stands in some forest types had not recovered to their initial carbon levels by the end of the 95-year simulation period (Table 6), especially in forest types MT7, MT9 and MT10. In most forest types, the difference in total stand carbon between treated and untreated stands declined over time since wildfire (Fig. 2); the exception is again in NI8, where differences increase over the simulation time period.

For those forest types where prescribed fire without mechanical harvest was simulated, results were intermediate between the untreated stands and the mechanically thinned stands (Fig. 3); that is, prescribed fire removed less carbon than mechanical fuel treatment, and total carbon following wildfire was greater in the prescribed burned stands than the mechanically thinned stands, but less than in the untreated stands.

Fig. 2 also shows the continued storage of carbon from harvested materials in wood products or in landfills, by forest type, taking into account the total quantity, species and size distribution of the harvested materials (curves with open circles). Addition of the carbon stored off-site in wood products or landfills increases the total carbon of the treated stands; the relative contribution to the total is minor but persistent. The carbon

Table 5
Effects of treatment on wildfire severity and intensity, mean and standard deviation.

Forest type	Fire characteristic	Untreated	Mechanical fuel treatment	Prescribed burn only
NI5	Flame length, m	8.88 ± 8.80	3.42 ± 5.28	n.a.
	Tree mortality, % basal area	74.86 ± 28.86	51.36 ± 31.32*	
	Stands burning in crown fire, %	50	14	
NI8	Flame length, m	10.04 ± 10.64	1.15 ± 0.22*	n.a.
	Tree mortality, % basal area	61.9 ± 40.05	13.9 ± 6.59*	
	Stands burning in crown fire, %	45	0	
MT2	Flame length, m	2.58 ± 5.21	0.46 ± 0.06	0.54 ± 0.13†
	Tree mortality, % basal area	36.93 ± 28.90	14.07 ± 4.70*	21.36 ± 7.98
	Stands burning in crown fire, %	14	0	0
MT6	Flame length, m	10.92 ± 9.13	1.29 ± 0.20*	5.96 ± 7.94*,†
	Tree mortality, % basal area	71.20 ± 38.40	16.88 ± 16.59*	47.64 ± 37.21*,†
	Stands burning in crown fire, %	60	0	28
MT7	Flame length, m	9.72 ± 7.25	0.97 ± 0.20*	n.a.
	Tree mortality, % basal area	87.56 ±17.26	58.56 ± 10.43*	
	Stands burning in crown fire, %	63	0	
MT9	Flame length, m	15.63 ± 9.91	1.80 ± 0.63*	3.83 ± 4.84*,†
	Tree mortality, % basal area	88.58 ± 20.62	46.33 ± 25.32*	66.46 ± 26.94*,†
	Stands burning in crown fire, %	75	4	12
MT10	Flame length, m	16.99 ± 5.22	n.a.	5.46 ± 3.94*
	Tree mortality, % basal area	97.12 ± 9.85		88.72 ± 17.71*
	Stands burning in crown fire, %	92		32

Mechanical fuel treatment includes thinning, pile burning of activity fuels, and, in MT2, MT6, MT9 and MT10, prescribed underburning. Stands burning in crown fire include those that were reported to burn in active crown fire, conditional crown fire (the stand supports active crown fire if the crown fire initiates in an adjacent stand, but will not support crown fire initiation due to lack of ladder fuels), and passive crown fire involving at least 50% of the trees. Stands burning in crown fire are reported as percent of total stands (no estimate of variability).

* Significant difference between treated and untreated stands.

† Significant difference between stands with mechanical fuel treatment and those with prescribed burn only ($p < 0.05$).

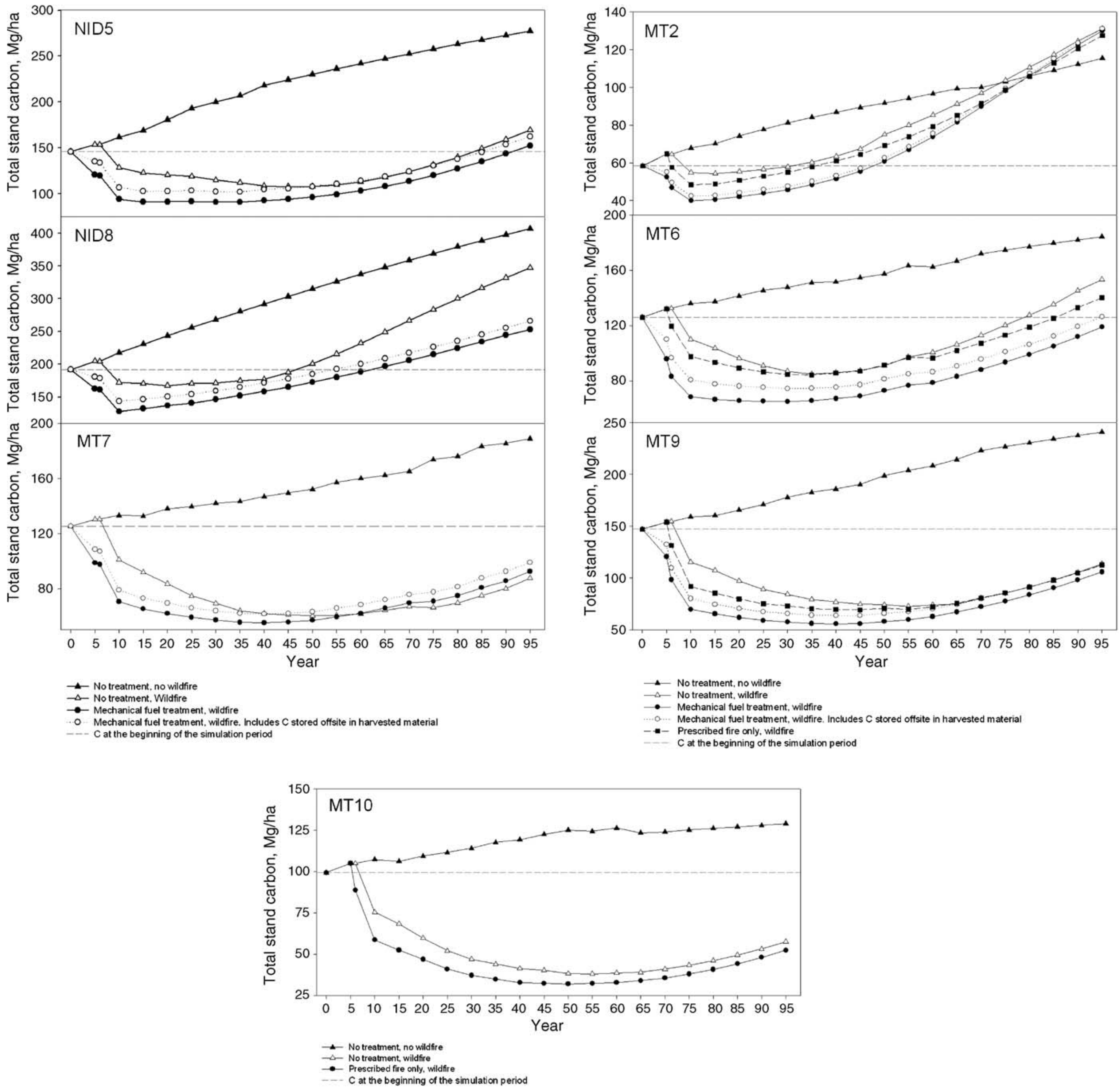

Fig. 2. Mean total stand carbon over time. Treatments were conducted in year five and six, wildfire occurred in year ten of the simulation.

content of energy used to remove the harvested material from the site and to produce wood products is not included in these results; if this information were available it would reduce contribution of the off-site carbon. The potential offset of carbon emissions from fossil fuels if harvest residues were used for energy production is also omitted from these results. If included, it would have the opposite effect. A fuller accounting of carbon implications would require detailed information about distance of the stands from processing facilities.

Although treated stands had less total carbon following wildfire than untreated stands, they had more carbon in live vegetation (Fig. 4) and less in dead, due to reduced fire-caused tree mortality (Table 5). The presence of more living trees after wildfire may explain why treated stands generally had smaller additional post-fire declines in carbon levels, and took less time after wildfire to become a net carbon sink.

4. Discussion

Results of this study indicate that fire intensity, severity, and impacts were reduced and stand resilience was enhanced by the fuel treatments. The results do not support the use of fuel treatments solely to protect carbon stocks or reduce emissions. Although wildfire emissions were reduced by fuel treatment, the fuel treatments themselves produced emissions, and the untreated stands stored more carbon than the treated stands even after wildfire. These results contrast with those of Hurteau et al. (2008), who suggested that prior thinning could have reduced CO_2 emissions from several large wildfires by 98%. Their analysis was limited to emissions from live vegetation however, typically a small part of the wildfire emissions in forest stands. Additional, significant emissions are generally produced from consumption of dead downed wood, litter and duff.

Table 6
Effects of wildfire on carbon in treated and untreated stands. Table values are mean and standard deviation.

Forest type	Fire effect	Untreated	Mechanical fuel treatment	Prescribed burn only
NI5	Wildfire C emissions, Mg/ha	32.5 ± 8.64	28.28 ± 7.16	n.a.
	Additional post-fire C decline, Mg/ha	30.72 ± 25.51	11.96 ± 13.11*	
	Years until site again becomes C sink	38.21 ± 17.28	30.71 ± 14.12	
	C in year 95, proportion of initial	1.12 ± 0.26	1.05 ± 0.31	
NI8	Wildfire C emissions, Mg/ha	44.90 ± 14.51	37.70 ± 15.11	n.a.
	Additional post-fire C decline, Mg/ha	25.26 ± 29.06	0*	
	Years until site again becomes C sink	23.00 ± 13.78	10.00 ± 0*	
	C in year 95, proportion of initial	1.89 ± 0.35	1.46 ± 0.42*	
MT2	Wildfire C emissions, Mg/ha	12.64 ± 6.74	7.57 ± 2.74*	9.71 ± 3.75
	Additional post-fire C decline, Mg/ha	4.38 ± 8.49	0.28 ± 0.63	0.45 ± 0.96
	Years until site again becomes C sink	11.43 ± 10.64	11.07 ± 2.13	11.43 ± 2.34
	C in year 95, proportion of initial	2.33 ± 0.64	2.31 ± 0.65	2.82 ± 0.64
MT6	Wildfire C emissions, Mg/ha	25.16 ± 10.32	14.28 ± 7.15*	22.24 ± 9.70†
	Additional post-fire C decline, Mg/ha	29.87 ± 23.67	4.17 ± 4.28*	17.43 ± 20.81†
	Years until site again becomes C sink	32.4 ± 14.44	23.60 ± 8.84*	29.00 ± 12.58
	C in year 95, proportion of initial	1.26 ± 0.24	1.02 ± 0.27*	1.17 ± 0.24†
MT7	Wildfire C emissions, Mg/ha	30.70 ± 13.08	25.67 ± 12.00	n.a.
	Additional post-fire C decline, Mg/ha	43.71 ± 24.03	17.09 ± 6.31*	
	Years until site again becomes C sink	52.41 ± 10.23	43.33 ± 6.79*	
	C in year 95, proportion of initial	0.96 ± 1.35	0.98 ± 1.34	
MT9	Wildfire C emissions, Mg/ha	42.17 ± 16.81	26.00 ± 9.61*	35.79 ± 12.48†
	Additional post-fire C decline, Mg/ha	45.04 ± 26.05	15.39 ± 8.38*	26.13 ± 17.97†
	Years until site again becomes C sink	47.50 ± 9.89	39.79 ± 6.99*	42.29 ± 9.44
	C in year 95, proportion of initial	0.82 ± 0.22	0.78 ± 0.22	0.82 ± 0.21
MT10	Wildfire C emissions, Mg/ha	30.44 ± 10.23	n.a.	26.08 ± 8.97
	Additional post-fire C decline, Mg/ha	39.77 ± 14.55		28.08 ± 10.17*
	Years until site again becomes C sink	54.40 ± 9.82		49.6 ± 7.35
	C in year 95, proportion of initial	0.62 ± 0.28		0.59 ± 0.26

Mechanical fuel treatment includes thinning, pile burning of activity fuels, and, in MT2, MT6, MT9 and MT10, prescribed underburning.
* Significant difference between treated and untreated stands.
† Significant difference between mechanical fuel treatment and prescribed fire alone ($p < 0.05$).

Only a limited amount of empirical work exists to assess effects of fuel treatment and wildfire on carbon stocks. Boerner et al. (2008) compared changes in observed carbon stocks following four treatments (control, prescribed fire, thinning, thinning and prescribed fire) at twelve study sites around the United States. They report that prescribed fire alone did not significantly reduce carbon stored in vegetation, but did reduce forest floor carbon. Mechanical thinning however, alone or in combination with burning, reduced carbon stored in vegetation. The post-treatment interval showed increased net carbon uptake in the thinned stands, indicating that the treatments enhanced the ability of the forests to absorb CO_2. The post-treatment interval was 2–4 years, and wildfire did not occur.

Our results show generally long recovery times, as well as differences in recovery times between forest types and treatments, and a large amount of variability within forest types and treatment, which can be assumed to be due to differences in initial stand structure and composition. Carbon recovery time was examined empirically by Rothstein et al. (2004), who studied jack pine stands in Michigan that typically burn in stand replacement fires. While they did not estimate fire-caused fuel consumption and emissions, they quantified carbon in standing trees, dead wood, and soil in 11

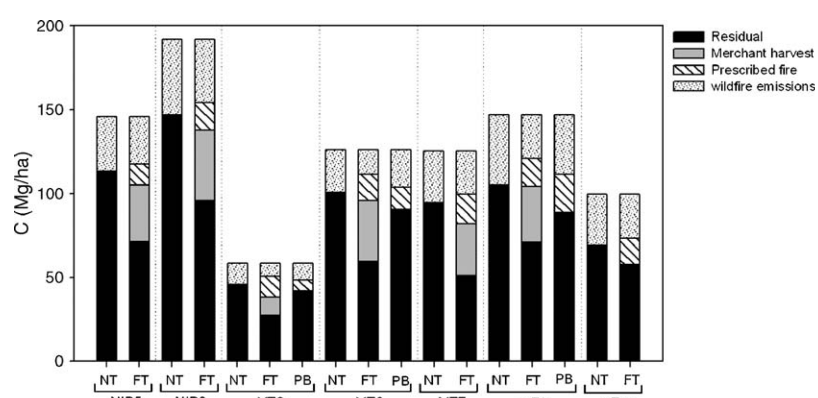

Fig. 3. Carbon stores and removals by forest type. The total height of the bar represents pretreatment carbon. Residual carbon is the carbon remaining after wildfire. Merchantable harvest is the material that is removed from the site. Wildfire emissions are the direct carbon emissions to the atmosphere at the time of wildfire. Prescribed fire emissions include emissions from piling and burning activity fuels as well as prescribed underburning where applicable. NT = no treatment, FT = mechanical fuel treatment (including post harvest prescribed fire in some forest types), PB = prescribed burn only.

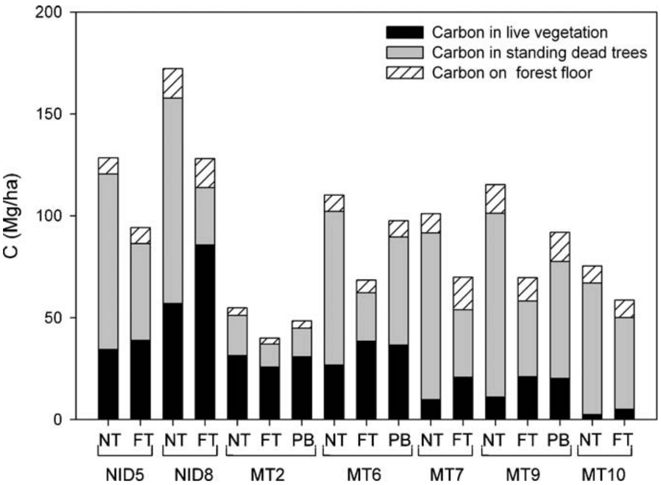

Fig. 4. Carbon after wildfire—means by treatment and forest type. The total height of the bar represents carbon on-site. Carbon in live vegetation includes carbon in live trees, including live roots, herbs and shrubs. Carbon in standing dead trees includes the carbon in dead roots as well as above ground. Carbon on the forest floor includes carbon in litter, duff, and dead and down woody material. NT = no treatment, FT = mechanical fuel treatment (including post harvest prescribed fire in some forest types), PB = prescribed burn only.

stands of varying ages. Their study shows a pattern of immediate decline in ecosystem carbon post-fire as dead woody material decomposed. The duration of decline was only 6 years in this forest type, after which increases in carbon stored in live vegetation offset further decomposition of dead wood, and total carbon stocks increased. In contrast, Dore et al. (2008) found that, 10 years after a stand replacement wildfire, a ponderosa pine site in Arizona was a net carbon source.

Fuel treatments can be expected to function best if they are designed to restore forest ecosystems so that fire can play its natural role (Baker, 1994; Covington et al., 1997; Fulé et al., 2001; North et al., 2009). This role will involve periodic losses of carbon to fire. Vegetation is dynamic, and so too are carbon pools at a particular site. Short term changes in carbon stocks at a site are ultimately less important than the ability of the site to continue to support forest vegetation and absorb atmospheric CO_2. Over a very long time horizon fire can be expected to visit a site periodically and carbon stocks will rise and fall repeatedly but probably without any cumulative net change (Kashian et al., 2006).

Although the unburned stands have higher levels of carbon than those burned by wildfire throughout the simulation period for most forest types (Fig. 2), fire exclusion is not a sustainable option for forests of the Interior West. Similarly, if fuel treatments are designed to exclude fire from western landscapes, then they ultimately put forest carbon stocks at greater risk. In the long run, disruption of fire's natural role on landscapes of the Interior West only serves to make forest resources more vulnerable to catastrophic fire. Even if fire suppression reduces emissions and increases carbon stocks temporarily, fire cannot be excluded indefinitely. In fact, the more successful fire suppression is in general, the less area will be burned under average conditions and more area will tend to burn under extreme conditions, when suppression is ineffective (Reinhardt et al., 2008). The inevitable result is that more area is burned in fewer, more unmanageable events with greater consequences, including higher carbon emissions, greater losses to biodiversity, and larger threats to communities and homes.

In the dry forests of the Interior West, perhaps the most sustainable and effective approach to forest management is restoration of fire dependent ecosystems so that they are less vulnerable to changes in disturbance under changing climatic conditions. For example, forest ecosystems that historically burned in low severity fire regimes but have experienced decades of fire exclusion are now burning in stand replacement fires (McKelvey and Busse, 1996). The effects of these fires in combination with summer drought that limits tree regeneration may convert forested landscapes in the dry interior western United States to grass and shrublands that typically store less carbon than forests. Restoration of fire to these landscapes under moderate burning conditions through the use of prescribed fire, while resulting in short term increases in emissions, may make these forests less vulnerable to catastrophic wildfire and ultimately maintain forest carbon stores (Hurteau and North, 2009).

The analysis reported here has a number of limitations. We simulated wildfire soon after the fuel treatments. Thus the effects of treatment we report are maximum effects. Over time the effects of fuel treatments on fire behavior, and on fire effects including effects on carbon stocks, would be expected to decline, as surface fuels accumulate and conifer regeneration results in a newly developing understory. A more complete picture of fuel treatment effectiveness could be obtained by simulating wildfire stochastically rather than at a fixed time after treatment. Future work could also include development of fuel treatment durability functions – an assessment of the rate at which fuel treatment effects decline over time in different forest types.

Because duff and woody fuels are extremely variable within forest type, and because they form an important portion of the on-site carbon in a stand, we expect our carbon estimates to be more accurate for the western Montana types, where duff and woody fuels were sampled, than in the north Idaho types, where they were estimated using rules embedded in FFE-FVS based on stand conditions and forest type.

Growth rates in FVS are sensitive to stand density, but do not reflect changes in nutrient availability that result from fire, therefore, the increased growth rates of stands following prescribed fire or wildfire are probably low-end estimates. This simulation does not incorporate effects of climate change on forest processes such as decomposition, regeneration or tree growth, or on disturbance dynamics. However, this study does provide a consistent method of looking at the direct consequences of management on forest carbon stocks.

This study is limited to stand-level effects of fuel treatment on carbon dynamics. Fire is a landscape-level process, however. Some studies (Ager et al., 2007; Finney, 2001) suggest that fuel treatments also provide off-site effects as landscape level patterns of fire extent, intensity and frequency may be altered by strategically placed treatments. If these off-site effects occur, they may increase the magnitude of fuel treatment effects in the short-run.

The treatments simulated in this study were uniform for all stands within a forest type, regardless of diameter distribution, species composition and fuels. In implementing fuel treatments however, managers could control effects by customizing prescriptions to meet particular objectives (which might include carbon retention) in a stand of a particular type and structure. Customizing treatment prescriptions using iterative model runs could increase their effectiveness. For example, repeated prescribed fires could be simulated, at varying intervals, to examine carbon impacts in a particular forest type. Thinnings could be simulated to a range of residual densities. Direct effects of the treatment and subsequent wildfire effects would depend in part on the initial stand structure and thinning intensity. Hoover and Stout (2007), for example, found that thinning from below increased plot level carbon stocks in mixed hardwood stands 25 years after treatment, but that other thinning treatments decreased carbon stocks compared to untreated plots.

The results of this study are simulated, not observed. They should be verified by longitudinal empirical studies. Meanwhile, FFE-FVS provides a consistent method of evaluating fuel treatment alternatives with respect to carbon and other effects. Because FFE-FVS is a tool that is available to land managers and fuel treatment planners, the methods presented here will allow users to develop treatments and consider carbon implications for their particular landscapes.

5. Conclusions

This paper provides data on carbon stored in stands of seven habitat type groups in the northern Rocky Mountains. It also provides estimates on direct effects of fuel treatments and wildfire on carbon stored in these stands. Simulated effects of treatment and of wildfire on carbon stocks are long-lasting. Fuel treatments reduce subsequent wildfire emissions but do not increase immediate post-wildfire carbon in the stands. However, fuel treatments reduce tree mortality from subsequent wildfire, enabling stand recovery and long term carbon uptake. Mechanical treatments also capture some carbon in off-site products. Fuel treatments in these forests are probably not usually justified solely from a carbon management standpoint; however, in some situations and particularly in the wildland–urban interface they are an important management tool for protecting homes and providing other forest benefits.

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