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Forest wildfire, fuel reduction treatments, and landscape carbon stocks: A sensitivity analysis

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ABSTRACT

Fuel reduction treatments prescribed in fire-suppressed forests of western North America pose an apparent paradox with respect to terrestrial carbon management. Such treatments have the immediate effect of reducing forest carbon stocks but likely reduce future carbon losses through the combustion and mortality caused by high-severity wildfires. Assessing the long-term impact of fuel treatment on the carbon balance of fire-prone forests has been difficult because of uncertainties regarding treatment and wildfire impacts on any given landscape. In this study we attempt to remove some of the confusion surrounding this subject by performing a sensitivity analysis wherein long-term, landscape-wide carbon stocks are simulated under a wide range of treatment efficacy, treatment lifespan, fire impacts, forest recovery rates, forest decay rates, and the longevity of wood products. Our results indicate a surprising insensitivity of long-term carbon stocks to both management and biological variables. After 80 years, a 1600% change in either forest growth or decomposition resulted in only a 40% change in total system carbon, and a 1600% change in either treatment application rate or efficacy in arresting fire spread resulted in only a 10% change in total system carbon. This insensitivity of long-term carbon stocks is due in part by the infrequency of treatment–wildfire interaction and in part by the controls imposed by maximum forest biomass. None of the fuel treatment simulation scenarios resulted in increased system carbon.

1. Introduction

Forest fuel reduction treatments can be an effective tool for mitigating the impacts of future wildfire on ecosystem services and restoring desirable structural attributes to fire suppressed forests. Growing appreciation of the role forest biomass plays in global carbon dynamics and associated climate change is forcing forest managers to consider the impact of any practice on the capacity of forests to hold carbon in organic form over time. Fuel reduction treatments (hereafter referred to simply as treatment) have posed an apparent paradox to forest managers in that their immediate impact is to reduce forest carbon stocks yet their intended effect is to protect biomass from wildfire combustion. Some authors have argued that the carbon saved from wildfire combustion eventually outweighs removals associated with treatment (Hurteau et al., 2008; Finkral and Evans, 2008; Hurteau and North, 2010; Stephens et al., 2009a). Others have suggested that the carbon saved by altering wildfire behavior is small compared to that removed in treatment (Campbell et al., 2012; Mitchell et al., 2009). The emerging narrative is that predicting the long-term carbon consequences of treatment and wildfire depends primarily on the parameters and time span used in the model simulations, and by extrapolation, varies profoundly from one fire-prone forest ecosystem to the next.

We believe this discussion currently lacks a simple yet comprehensive sensitivity analysis wherein one can quantitatively assess the long-term, landscape-scale consequences of fuel reduction treatments and wildfire on forest carbon stocks over a broad range of conditions, including various rates of forest growth and decomposition, treatment efficacy at reducing future fire extent and severity, wildfire effects, and forest product longevity. In this type of sensitivity analysis we are freed from the burden of precisely defining site-specific variables (such as growth and regeneration rates) or poorly understood parameters (such as wildfire combustion efficiencies or treatment lifespan). Rather we need only explore a range of such variables generally agreed to include the values realized by most fire-prone and fire-suppressed forests in which fuel reduction treatments are being, or considered being, prescribed. In this paper we present just such an analysis.

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Our specific objectives were to evaluate the dynamic accumulation of carbon in forest biomass, forest necromass, and wood products over 80 years for an entire landscape of fire-prone forest separately over a broad range of:

1. Treatment application rate (fraction of the landscape from which fuel was reduced annually)
2. Treatment efficacy (both with respect to reducing wildfire spread and reducing wildfire effects)
3. Wildfire effects (combustion and tree mortality in both treated and untreated stands)
4. Forest growth and re-establishment rates
5. Forest decomposition rates (from burned stands, unburned stands, and wood products generated in treatment activities)

We developed the model with data from a specific fire-prone landscape in eastern Oregon, and subsequently manipulated the five variables above by a factor of 16. In doing so we elucidate basic system behavior germane not only to our initial forest, but all arid fire-prone forests, as well as any other forests that may fall within these deliberately wide margins of parameterization.

2. Methods

2.1. Overall approach

Details regarding our approach to carbon modeling, landscape scaling, and sensitivity analysis are described in separate sections 2.2–2.5. In brief, we examined the relative effects of treatment rate, treatment efficacy, wildfire impacts, forest growth, and forest decay on forest carbon dynamics for 2000 randomly selected locations within the fire-prone Deschutes National Forest. Using a combination of spatially explicit data sources, we assigned values to each point for initial biomass, necromass, and maximum biomass potential. Each of these plots was then subjected to a process model which tracks annually, net primary production, harvest, mortality, combustion, and decomposition for 1024 unique temporal combinations of treatment and wildfire over an 80 year simulation period (chosen to accommodate four 20-year extreme fire events). Whole landscapes, representing alternate disturbance histories, were then assembled by selecting, weighting, and summing the 80-year plot-level simulations to reflect various user-defined treatment rates, wildfire frequency, and treatment efficacy. This simple ensemble approach made it easy to compare landscapes resulting from different disturbance regimes, while implicitly accounting for protracted repeated treatment and the resulting distribution of time lags between treatment and wildfire exposure. Subsequent sensitivity analysis was conducted by repeating the exercise over a 16-fold range of key input parameters.

2.2. Initialization of forest structure

While our modeling efforts necessarily begin with a real forest landscape (typical of that where fuel reduction treatments are prescribed), our purpose here is to manipulate input parameters well beyond site-specific defaults. In doing so, our overall sensitivity analysis is intended to have relevance to all fire-suppressed, fire-prone forests wherein reduction treatments are considered.

Our initial model input reflected current forest conditions on the Deschutes National Forest located in central Oregon, USA. Both the site characteristics and disturbance history of the Deschutes National Forest are representative of many suppressed and fire-prone forests of western North America wherein extensive fuel reduction treatments are being employed to reduce the severity and spread of wildfire.

A sample of 2000 30 × 30 m plots randomly selected within the Deschutes National Forest were assigned initial carbon pools and maximum achievable biomass based on existing fuel structure and biomass maps, in some cases optimized to reflect the distribution of values found in stem-level forest inventory data (see Online supporting Table A). These 2000 sample points were then duplicated by a factor of 10 and arbitrarily assigned an area of 1 ha. The result was a non-spatially-explicit population of forest plots, amounting to 20,000 artificial hectares and collectively representing the distribution of forest structure and growth capacity of the Deschutes National Forest.

2.3. Forest process model

Fig. 1 illustrates the mass flow process model used to simulate aboveground net primary production (ANPP), harvest removals, fire and non-fire mortality, decomposition, and combustion of nine separate carbon pools at annual time steps. The recognized pools are foliage (leaf), branch (woody structure ≤ 5 cm diameter), and bole (woody structure > 5 cm diameter) in the form of forest biomass (live plant matter), forest necromass (dead plant matter), and forest products (dead plant matter taken off-site). Live biomass pools are allowed to aggrade annually toward a site-specific maximum according to the Chapman–Richards function illustrated in Fig. 2c, and described:

$$BM = a^{*}(1 - \exp(-b_1 x_1))^{c} \quad (1)$$

where BM is aboveground live biomass in kg C m^{-2}, a is the maximum aboveground live biomass that the site can sustain, x_1 is the time in years since initiation (back-calculated from estimates of current biomass), b_1 is a constant proportional to the time required to achieve maximum biomass, and c is a constant proportional to the initial growth lag. Decomposition (the heterotrophic mineralization

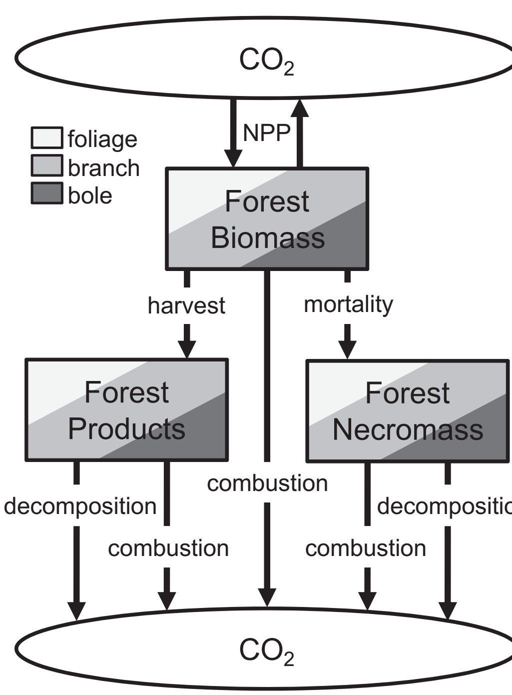

Fig. 1. Basic model structure. This simple forest carbon model tracks net primary production (NPP), harvest removals, fire and non-fire mortality, decomposition, and production through nine separate pools at annual time steps. The nine recognized pools are foliage (leaf), branch (woody structure ≤ 5 cm diameter), and bole (woody structure > 5 cm diameter) in the form of forest biomass (live plant matter), forest necromass (dead plant matter), and forest products (dead plant matter taken off-site).

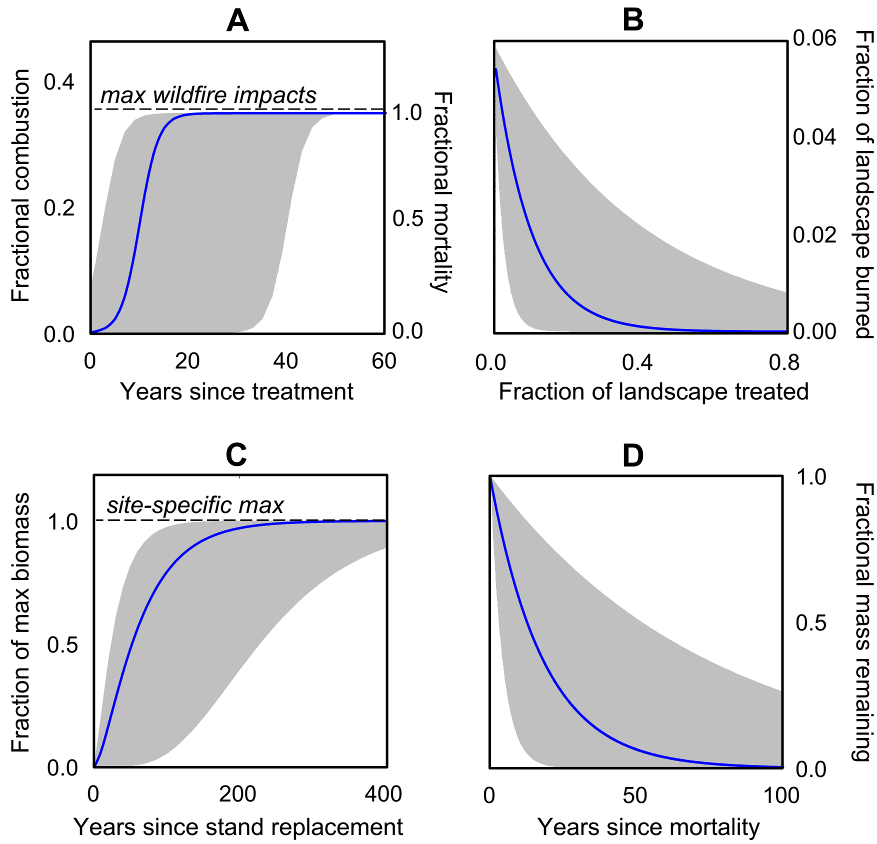

Fig. 2. Equations used to represent plot-level treatment efficacy as a function of time since treatment (A, see also Equation (3)), landscape-level treatment efficacy as a function of area treated (B, see also Equation (6)), forest fuel accumulation as a function of time since disturbance (C, see also Equation (1)), and necromass decomposition as a function of time since mortality (D, see also Equation (2)). Blue lines are the default parameterization, gray areas cover the 16× range over which these functions were manipulated for sensitivity analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of each necromass and forest product pool) was computed according to an exponential loss function illustrated in Fig. 2d and described below:

$$D = M^{*} - k \tag{2}$$

where D is the loss to decomposition of necromass or forest product in kg C m^{-2} yr^{-1}, M is the current mass of necromass or forest product in kg C m^{-2}, and k is a pool-specific decomposition constant. The specific values used to parameterize equations (1) and (2) are detailed in Online supporting Table B. Wildfire effects, which include fractional overstory mortality and separate combustion efficiencies for each fuel biomass pool are determined according to the sigmoidal function illustrated in Fig. 2a and defined below:

$$\mathrm{FE}_{\mathrm{real}} = \mathrm{FE}_{\mathrm{min}} + (\mathrm{FE}_{\mathrm{max}} - \mathrm{FE}_{\mathrm{min}})/(1+\exp(-(x_2-(L/2))/2)) \tag{3}$$

where $\mathrm{FE}_{\mathrm{real}}$ is the realized fire effect (fractional overstory mortality or fractional combustion), $\mathrm{FE}_{\mathrm{min}}$ is the minimal effect incurred immediately following treatment, $\mathrm{FE}_{\mathrm{max}}$ is the maximum effect incurred once fire hazard returns to pre-treatment levels, x_2 is time since treatment in years, L is the treatment effective lifespan in years. Equation (3) is especially useful since it allows the consideration and manipulation of wildfire effects, treatment efficacy in altering wildfire behavior, and treatment lifespan using only three parameters. The specific values used to parameterize equation (3) are detailed in Online supporting Table C.

2.4. Defining landscape disturbance regimes

Up-scaling from the plot-level simulations to an entire landscape was achieved by first subjecting each individual plot to 1024 unique temporal combinations of treatment and wildfire over the 80 year simulation period. That is, combinations of wildfire or no wildfire and treatment or no treatment, were applied in each of five 20-year intervals either 1, 6, 11, or 16 years prior to wildfire exposure. The output from each of these model runs was then weighted by the probabilistic landscape fraction of these unique disturbance histories calculated from user-defined treatment rates, wildfire frequency, and treatment efficacy using equations (4) and (5):

$$T_1 = \mathrm{TR} \times \mathrm{FI} \tag{4}$$

$$T_2 = T_1 \times (\mathrm{LS}_1/\mathrm{FI}) \tag{5}$$

$$\mathrm{WF} = \alpha \times \exp(-\beta \times T_2) \tag{6}$$

where T_1 is the probability of a plot being treated during an extreme wildfire return interval, TR is the fraction of landscape treated annually, FI is the extreme wildfire return interval (default = 20 years for these simulations), T_2 is the probability of a treated plot being effective in reducing extreme wildfire spread, LS_1 is the effective lifespan of a treatment in reducing extreme wildfire spread, WF is the fraction of the landscape affected by an extreme wildfire which was imposed at 20 year intervals. Default parameters for equations (4)–

(6) are given in Table 1 and Online supporting Table C. Illustrated in Fig. 2b, the parameters defining the negative exponential relationship between area effectively treated and the final size of wildfires burning under extreme weather conditions (α = 0.0595, and $\beta = 99.3673$ in equation (6)) were derived from spatially explicit fire spread simulations conducted by Finney et al. (2007) for a Montana landscape of similar climate, topography, and forest composition as the Cascadian landscape investigated here. As such they provide an adequate starting point from which to explore a range of such curves. For ease of computation, extreme wildfire events were imposed evenly throughout the 80 year simulation period (i.e., on years 20, 40, 60, and 80). Additional simulations using stochastic fire intervals (not shown) demonstrate empirically what one would expect, namely, that once scaled over multiple cycles, median system behavior is identical for stochastic and regular fire intervals.

2.5. Sensitivity analysis

Our approach to sensitivity analysis began with identifying reasonable and representative literature values for the various parameters defining treatment intensity, treatment efficacy, wildfire effects, forest growth and decay. As shown in Fig. 2, these default values were then manipulated by factors of 0.25, 0.5, 1, 2, and 4. In some cases, individual variables were treated as perfect covariates (e.g., the doubling of treatment effective lifespan in arresting fire spread across the landscape, involved the doubling of treatment effective lifespan in influencing plot-level fire effects). In other cases, where factors were not defined by a single linear variable (e.g., the non- linear function parameters defining forest growth or the relationship between area effectively treated and the final size of wildfires burning under extreme weather conditions) parameter estimates approximated the desired two-fold multiples. Details regarding default parameter values, and their 16× manipulation are given in Table 1.

For heuristic reasons, the range of variables employed in our analysis was purposefully regular. Still, certain combinations of fire effects, treatment intensity, and treatment efficacy coincidentally describe particular goal-driven treatment strategies used for managing landscape fire risk. For instance, minimum treatment efficacy applied over maximum area describes a system of low-hazard fire containment designed to encourage large, low-severity wildfire as part of restoring natural fire regimes. By comparison, maximum treatment efficacy applied over minimum area describes a system of high hazard fire containment designed to arrest the spread of high-severity wildfire. Finally, moderate treatment efficacy applied over small areas describes a system where restoration of natural fuel breaks is used to encourage a mix of moderate- and low-severity wildfire to meet both restoration and protection goals.

Table 1
Manipulation of key model parameters for sensitivity analysis.

Model input variable	Factor				
	0.25×	0.5×	(default) 1×	2×	4×
Treatment removals (fraction of biomass)[a]	0.08	0.17	0.33	0.66	0.83
Treatment application rate (landscape fraction yr^{-1})[b]	0.0025	0.005	0.01	0.02	0.04
Treatment effective lifespan (L in Eq. (3))					
In altering plot-level fire effects (yr)[c]	5	10	20	40	80
In arresting landscape fire spread (yr)[d]	2.5	5	10	20	40
Capacity of treatment to arrest fire spread (β in Eq. (6))[e]	2.5	5	10	20	40
Wildfire effects (FE_{min} and FE_{max} in Eq. (3))[f]					
Mortality (fraction live biomass)	0.25	0.50	0.999	0.999	0.999
Max live leaf combustion (fraction)	0.25	0.50	0.999	0.999	0.999
Max live branch combustion (fraction)	0.025	0.05	0.1	0.2	0.4
Max live bole combustion (fraction)	0.013	0.025	0.05	0.1	0.2
Max dead leaf combustion (fraction)	0.25	0.5	0.999	0.999	0.999
Max dead branch combustion (fraction)	0.25	0.5	0.999	0.999	0.999
Max dead bole combustion (fraction)	0.125	0.25	0.5	0.999	0.999
Forest decomposition rate (k in Eq. (2))[g]					
Leaf (fraction yr^{-1})	0.025	0.05	0.1	0.2	0.4
Branch (fraction yr^{-1})	0.01	0.02	0.04	0.08	0.16
Bole (fraction yr^{-1})	0.0025	0.005	0.01	0.02	0.04
Post-disturbance growth[h]					
Forest reestablishment rate (c in Eq. (1))	6.4	3.2	1.6	1.5	1.4
Forest growth rate (b_1 in Eq. (1))	0.01	0.015	0.02	0.03	0.04
Wood products decomposition rate (fraction yr^{-1})[i]	0.0013	0.0025	0.005	0.01	0.02

The specific input variables collectively defining treatment effective lifespan, wildfire effects, forest decomposition, and post-disturbance growth were assumed to perfectly co-vary with another; by example, when simulating 2× forest decomposition, leaf, branch, and bole factors were all doubled. Note that in the case of wildfire effects, some variables saturate near their default value prohibiting a true 2× or 4× scenario. In the case of fire spread and forest growth coefficients, these unitless variables can only approximate even multiples. Parameter midpoints were chosen to be representative of arid, fire-prone forests of western North America and the fuel reduction prescriptions commonly employed during the last two decades based on simplified central tendencies reported by:

[a] North et al. (2007), Stephens et al. (2009b).
[b] Finney et al. (2007).
[c] Rhodes and Baker (2008).
[d] Lacking any empirical data, this is assumed to be one half the plot-level lifespan.
[e] Finney et al. (2007), Campbell et al. (2012).
[f] Fahnestock and Agee (1983), Campbell et al. (2007).
[g] Harmon and Sexton (1996), Parminter (2002), Campbell et al. (2008).
[h] Modeled using BIOMEBGC according to Turner et al. (2007).
[i] Finkral and Evans (2008), Harmon et al. (1996).

3. Results

3.1. Plot-level model evaluation

While our primary objective is to evaluate the sensitivity of landscape carbon pools and fluxes to various levels of treatment and fire effects, it is valuable to visualize how such events play out over time at a single plot, if only to confirm that our model responded as intended. Fig. 3 shows how live biomass, forest necromass, and wood product mass change for one representative plot experiencing default levels of fuel reduction treatment, wildfire, both, and neither. Qualitatively, our model responds as it was intended to. Specifically, treatment reduces live biomass by transferring it to the wood product pools, wildfire reduces live biomass through combustion and transfer to forest necromass, treatment prior to wildfire reduced the impacts of wildfire, and without any disturbance, forest carbon stabilizes near the site-defined maximum.

3.2. Sensitivity of landscape disturbance history to fuel treatment variables

Fig. 4 shows the cumulative area, over 80 years, affected by treatment, wildfire, or no disturbance across a 16× range of

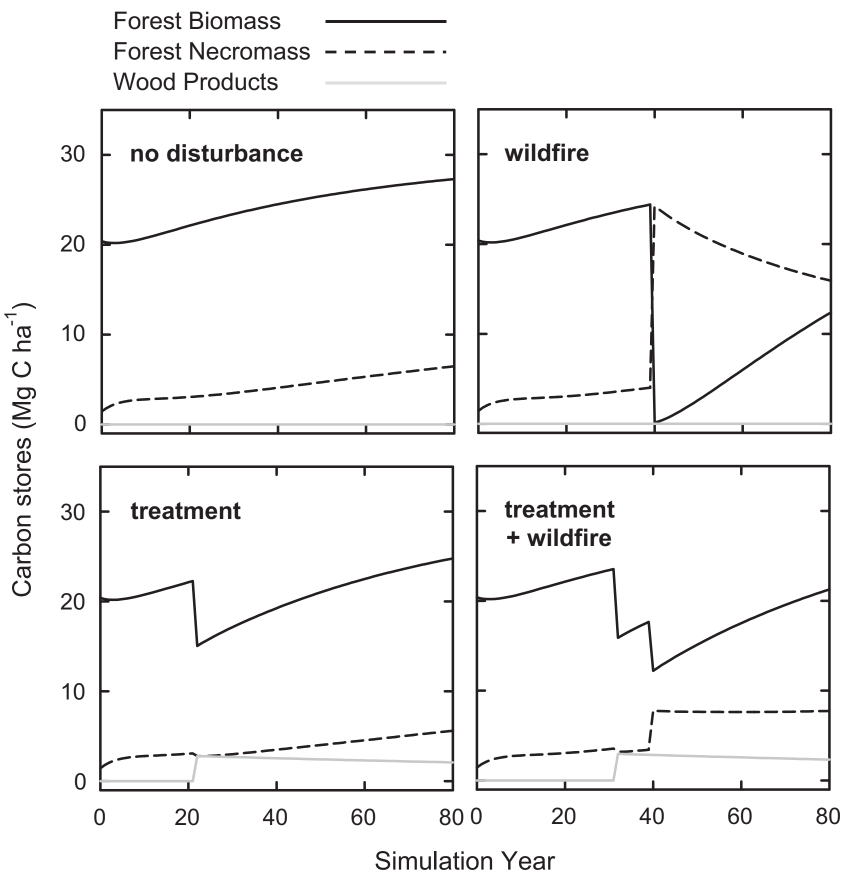

Fig. 3. Carbon stores simulated for a single representative plot undergoing various combinations of fuel treatment and wildfire. Severe wildfire in an untreated stand transfers nearly all biomass into necromass. Treatment alone transfers a portion of biomass into wood products. Treatment prior to wildfire greatly reduces the impact of wildfire.

treatment application rate, treatment effective lifespan, and treatment efficacy in arresting wildfire spread over periods of extreme behavior. As treatment application rate increases from 0.25 to 4% per year, the fraction of the landscape impacted by wildfire drops from approximately 20% to almost zero. This very strong response of area burned to area treated reflects the power of strategically placed treatment to arrest wildfire spread (Equation (3)). However, it is important to appreciate that this nearly 95% reduction in area burned amounts to only 200 ha across our 2000 ha landscape and came at the cost of treating nearly 1600 ha. The landscape response to variation in treatment effective lifespan is almost identical to that of treatment application rate. This stands to reason, since treatment duration and frequency contribute equally to the fraction of landscape effectively treated during a wildfire event.

The efficacy of treatment in arresting wildfire spread (determined in our model with the β coefficient of Equation (3) and distinct from the treatment efficacy in reducing plot-level fire severity) has a predictably strong effect on the cumulative area subject to wildfire. However, just as treatment application rate, and lifespan, the absolute reduction in area burned is very small compared to the area treated or undisturbed. As we will see later in our sensitivity analysis, this discrepancy between the proportional response (defined by the conditional process interaction) and the absolute response (defined by the conditional process interaction multiplied by the probability of such an interaction occurring) is very important.

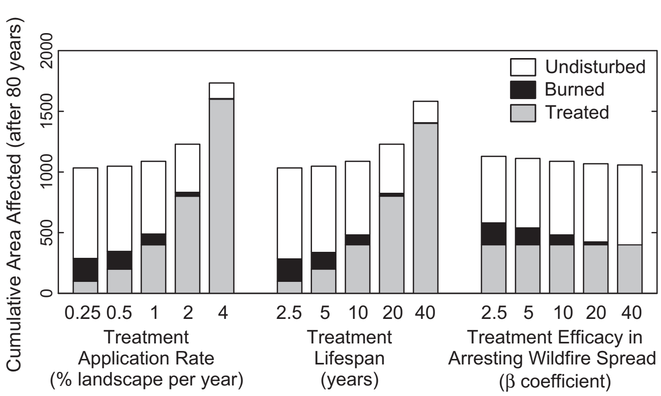

Fig. 4. Simulated effect of treatment parameters on the cumulative landscape area treated, burned, and left undisturbed over 80 years. Multiple burning, treatment or both at the same locations are tallied cumulatively; as such, total area disturbed after 80 years is not equal across treatment regimes. Note that in all but one extreme case the cumulative area treated exceeds the cumulative area burned even though the model accounts for the ability of treatment to reduce burn probability in untreated locations. Note also that default values of treatment application rate, lifespan, and efficacy result in more undisturbed area than cumulative treatment and burning combined.

3.3. *System sensitivity to fuel treatment variables*

A full accounting of sensitivity to various treatment parameters appears in Table 2, with the more salient responses illustrated in Fig. 5. The responses most tightly coupled to treatment parameters are the mass of wood products and their subsequent decomposition. Over a 16× range, increased treatment application increased the forest product pool, and the decay thereof, at a nearly 1:1 ratio.

Table 2
Sensitivity of landscape carbon fluxes and pools to key model parameters.

Response variable	Input variable which was manipulated 16× from 0.25 default value to 4× default value							
	Treatment removals	Treatment application rate	Treatment effective lifespan	Treatment efficacy in arresting fire spread	Wildfire combustion and mortality	Forest decomp. rate	Wood products decomp. rate	Postdisturbance regeneration and growth rate
Landscape C fluxes								
Net primary production	0.07	0.07	0.07	−0.06	0.06	−0.06	−0.06	0.24
Heterotrophic respiration	−0.06	−0.07	−0.07	−0.07	0.06	0.14	−0.06	0.10
Wood product loss	0.59	0.96	0.85	0.07	−0.06	−0.06	0.10	0.10
Prescribed combustion	0.23	0.90	0.81	−0.06	−0.06	−0.09	−0.06	0.10
Wildfire combustion	0.07	−0.72	−0.63	−1.49	0.51	−0.17	0.07	0.12
Landscape C pools								
Forest biomass	−0.07	−0.07	−0.07	0.07	−0.06	−0.06	−0.06	0.10
Forest necromass	−0.06	−0.08	−0.08	−0.07	0.06	−0.21	−0.06	0.09
Wood products	0.60	0.97	0.80	0.06	−0.06	−0.06	−0.10	0.09
System total	−0.06	−0.07	−0.07	0.06	−0.06	−0.08	−0.06	0.10

The sensitivity quotients shown here represent the linear fraction by which the output variable changes relative to the fractional change in input variable. Specifically, the absolute value of these sensitivity quotients = $(\text{Input}_{max}/\text{Input}_{min})/(\text{output}_{max}/\text{output}_{min})$, where $(\text{Input}_{max}/\text{Input}_{min})$ always equaled 4/0.25. Absolute quotients of one denote 1:1 sensitivity, absolute quotients greater than one represent hypersensitivity, absolute quotients less than one represent insensitivity. After computation, quotients received a negative or positive sign depending on the directional relationship between input and output variable. Pools and fluxes are limited aboveground components.

A similar relationship exists between treatment parameters and carbon combustion, with increases in application rate, lifespan, and efficacy in arresting wildfire spread all resulting in near 1:1 increases in prescribed combustion and reductions in wildfire combustion. These emergent relationships between treatment levels, wood product pools and forest combustion over space and time are not that notable; by themselves, these results do little more than validate the direct functionality of treatment in our model. Much more profound is the striking insensitivity of landscape-wide carbon stocks to treatment. As shown in Table 2, the response of NPP, forest decomposition, forest biomass, and forest necromass, to treatment level, live span, and efficacy were all below 0.10:1. In other words, over a 16× range of treatment level, forest carbon stocks and fluxes changed by less than 2×. The finding that landscape carbon pools are largely insensitive to large changes in parameters such as treatment application rate and subsequent wildfire combustion was not expected. The reason lies in landscape scaling and the disproportional rarity of wildfire. For instance, a

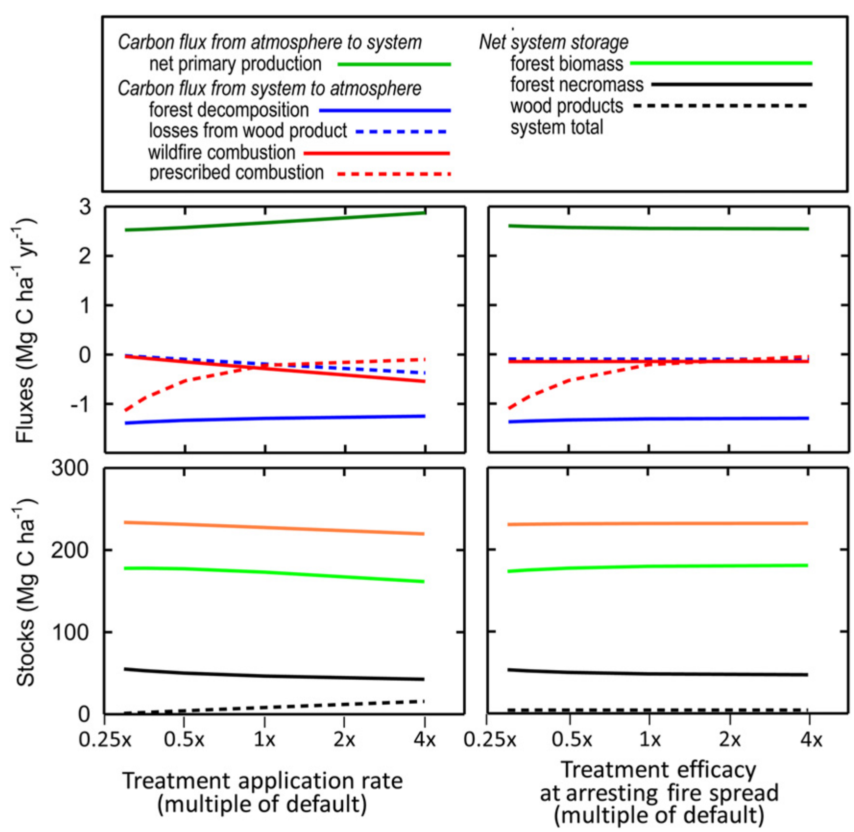

Fig. 5. Simulated response of landscape carbon stocks and fluxes to a 16× range of treatment application rate and efficacy in arresting fire spread. Carbon stores and fluxes represent the 80 year average of 500 locations randomly selected from the study landscape. The wood product pool increases with increasing treatment rate but fails to compensate for losses in the live and dead forest pools causing total system carbon to decrease with increasing treatment application rate. Default treatment application rate was 1% of the landscape annually. Default treatment efficacy at arresting fire spread is a *b* value of 10 in equation (3).

doubling of treatment (either in application rate, lifespan, or capacity to alter wildfire behavior) reduces the impacts of wildfire by half, but since wildfire is influencing such a small portion of the landscape, the absolute impact of treatment on wildfire across the landscape ends up being very small. Recall that a nearly 95% reduction in area burned across our 2000 ha landscape amounted to less than 200 ha (see Fig. 3).

This attenuation of treatment effect as one scales from the plot to the landscape is especially important with respect to over-all carbon stocks. While no level of treatment results in there being more system-wide carbon than a completely untreated landscape (Fig. 5), the long term over-all carbon costs are very small. In our simulations, increasing treatment application rate 16× from 0.25 to 4.0% of the landscape annually reduced system carbon stocks (averaged over 80 years) by only 10%.

3.4. System sensitivity to forest growth and decay

A full accounting of system sensitivity to forest growth and decay appears in Table 2, with the more salient responses illustrated in Fig. 6. Through its direct effect on NPP, increases in forest establishment and growth rates lead to increases in forest biomass and necromass. Due to there being more biomass and necromass on site at any given time, increases in forest establishment and growth had the secondary effect of increasing overall combustion, however, the effect was almost negligible since it was realized only on the proportion of the landscape affected by fire. Note that these responses are generally more important in driving carbon pools and fluxes than the rates of combustion and mortality incurred in a wildfire.

4. Discussion

4.1. Fuel reduction treatment and wildfire occurrence

Empirical confirmation that fuel reduction treatment reliably influences large-scale fire behavior remains elusive. However, fuel reduction treatments by design are effective in reducing the risk of high-severity fire at the stand level (Agee and Skinner, 2005; Ager et al., 2007; Stephens et al., 2009b), and carefully parameterized modeling exercises employed to quantify the effects of fuel treatment on fire spread across the landscape suggest a strong capacity of strategically-placed treatment to reduce the overall size of a single wildfire (Miller, 2003; Finney et al., 2007; Ager et al., 2007). By incorporating these relationships into a simple forest carbon model, we show the amount of forest biomass killed and combusted by wildfire across a landscape is strongly influenced by fuel reduction treatment. The parameter most responsible for this turned out to be the coefficient describing the negative exponential relationship between area treated at the time of a wildfire and the eventual size of that wildfire burning under extreme conditions (described by Finney et al., 2007; expressed in this paper as Equation (3)).

4.2. The insensitivity of carbon stocks

The most profound outcome of this study was the relative insensitivity of system-wide carbon stocks to most of our model variables. After 80 years, a 1600% change in either growth or decomposition resulted in only a 40% change in total system carbon, and a 1600% change in either treatment application rate and

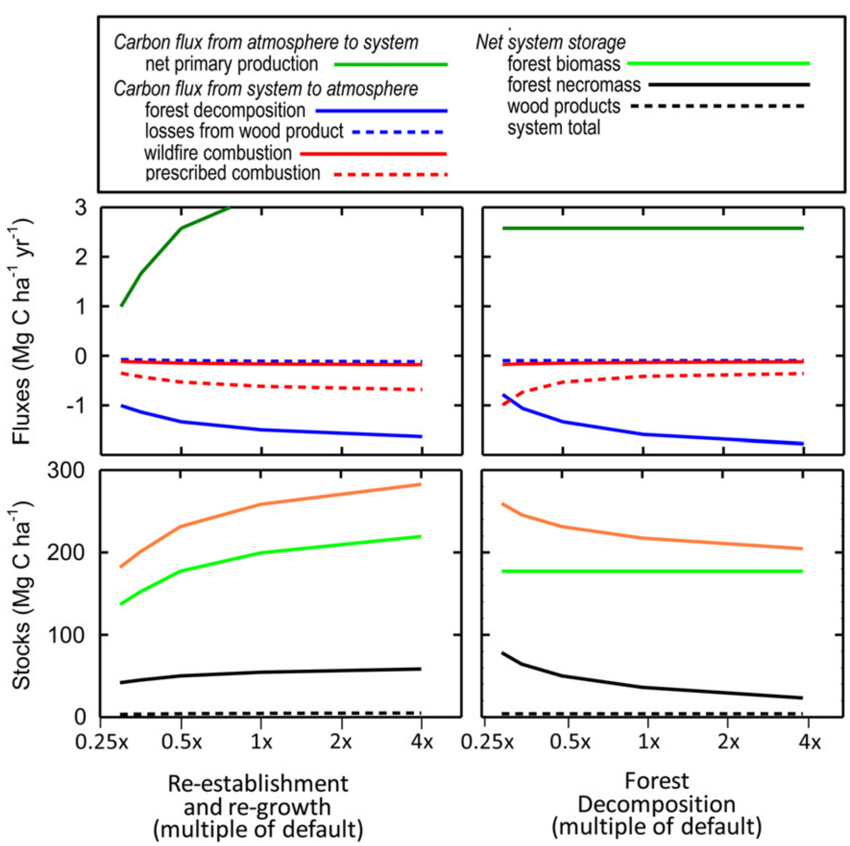

Fig. 6. Simulated response of landscape carbon stocks and fluxes to a 16× range of forest decomposition and the rate of post-fire reestablishment and growth. Carbon stores and fluxes represent the 80 year average of 500 locations randomly selected from the study landscape. Default re-establishment and re-growth are values of 0.02 for b and 1.6 for c in Equation (4). Default forest decomposition rates are k-constants of 0.01, 0.04, and 0.10 yr^{-1} for bole, branch, and foliage, respectively.

efficacy in arresting fire spread resulted in only a 10% increase in total system carbon (Fig. 5). Given that carbon stocks are the dynamic balance between inputs via forest growth and outputs via combustion and decomposition (both on-site and in forest products), how is it that carbon stocks can be so insensitive to changes in these variables? Dissecting the system behavior reveals two primary reasons.

First, there is the issue of relative versus absolute area subject to wildfire. As discussed earlier, even small changes in treatment rate can dramatically influence the amount of area impacted by a wildfire, but wildfire is simply not that common to begin with. Among fire-prone forests of the western US, the combination of wildfire starts and suppression efforts result in current average burn probabilities of less than 1% (Campbell et al., 2012; Rhodes and Baker, 2008). In our simulations, where extreme-weather wildfires were ignited once every 20 years, a 95% reduction in burned area amounted to only 200 ha across our 2000 ha landscape (see Fig. 4). Simply put, even when treatment is presumed efficient and effective, there is not that much to affect.

Second, there is the functional redundancy between fuel reduction treatment and wildfire. Both fuel treatment and wildfire result in the combustion of fine fuels; both fuel treatment and wildfire transfer living and growing wood mass into dead and decomposing wood mass; and the collective residence time of wood products is not profoundly different than that of dead wood in the forest (Krankina and Harmon, 2006). Consequently, actions that shift the flow of carbon away from wildfire combustion and on-site decomposition toward prescribed combustion and off-site decomposition are limited in their ability to alter system wide carbon stocks. Simply put, fuel reduction treatment moves carbon in a similar way to wildfire.

4.3. Lessons learned from sensitivity analysis

Much uncertainty regarding the impacts of fuel treatment on future combustion losses arises from uncertainty in the ability of various prescriptions to alter stand-level wildfire behavior. The sensitivity analysis we present here suggests that neither treatment efficacy nor lifespan at the stand-level is especially important in altering long-term landscape-wide carbon stocks. Expanding the range of these inputs well beyond the above-mentioned literature values altered the 80 year average system-wide carbon stock by less than 10%. Our observation that long-term, system-wide carbon stocks are influenced much more by the capacity of fuel treatment to arrest wildfire spread to adjacent stands than stand-level efficacy in reducing fire impacts, supports the notion that treatment placement is much more important than treatment intensity (Finney, 2007).

A more predictable, yet still important observation is the importance of forest growth rates and maximum biomass potential before and after both treatment and wildfire. Kashian et al. (2006) suggest that the density of post-fire re-growth was more important in dictating long-term carbon stocks across the greater Yellowstone ecosystem than was the frequency or intensity of fire. Similarly, our sensitivity analysis found the rate at which forests re-established after fire was more important to maintaining long-term carbon stocks than either disturbance frequency or intensity.

Our liberal manipulation of treatment and forest response parameters was intended to be inclusive of all arid fire-prone forest on which fuel treatments are being applied. However, our simulations did assume that after treatment or wildfire, all locations followed some successional trajectory toward that location's pre-disturbed condition. As such, our conclusions do not consider fire or treatment-induced state-change, which may affect carbon stocks by permanently altering the balance between growth and mortality (see Johnson and Curtis, 2001; Bormann et al., 2008). Conclusions presented here do not apply to systems where wildfire effect transition away from forest or semi-permanent reductions in production capacity (Campbell et al., 2012).

4.4. Implications

By design, our analysis did not explicitly consider specific fuel treatment systems. However, in manipulating our treatment efficiency equations (1) and (6) we did isolate the intended effect of various fuel treatment systems and their relative impact on carbon stocks. As described in Table 3, strategic restoration systems (intended to encourage a mix of high- and low-severity fire and restore landscape composition) and high-hazard fire containment systems (intended to arrest the spread of high-severity fire) result in intermediate landscape carbon stocks compared to low-hazard fire containment systems (intended to encourage large low-severity fires) which result in relatively lower carbon stocks, or complete fire suppression which result in the highest carbon stocks.

There is a strong consensus that large areas of arid forests in the western U.S. have suffered both structurally and compositionally from a century of fire exclusion (Schoennagel and Nelson, 2010) and that fuel reduction treatment including tree thinning and prescribed fire can be an effective tool for restoring historical functionality and resilience to some of these ecosystems (Agee and

Table 3
Relative consequences of various fuel treatment systems on landscape carbon stocks inferred from the sensitivity analysis.

Fuel treatment system and objective	Efficacy in altering plot-level fire behavior	Efficacy in arresting landscape fire spread	Fraction of landscape treated	System-wide carbon stocks[a]
No treatment				
Suppression of all wildfire	None	None	None	Highest
Low-hazard fire containment[b]				
Encourage large low-severity fire while minimizing high-severity fire	Moderate	Low	High	Lowest
High-hazard fire containment[c]				
Arrest the spread of high-severity fire by maintaining defensible fuel breaks	High	High	Low	Intermediate
Strategic restoration[d]				
Encourage a mix of high- and low-severity fire to restore landscape structure and composition	Moderate	Low	Moderate	Intermediate

[a] Sum of biomass, forest necromass, and wood products across entire landscape, averaged over 80 years.
[b] As considered for the Sierra Nevada by North and Hurteau (2011).
[c] As considered for the Rocky Mountains by Reinhardt and Holsinger (2010).
[d] As might be appropriate for the Klamath Siskiyou region, Halofsky et al. (2010).

Skinner, 2005; Ager et al., 2007; Stephens et al., 2009b). The notion that thinning and prescribed burning of such forests have the added benefit of increasing long-term carbon stocks through the reduction of wildfire mortality and combustion is not supported by our modeling exercises. Instead, our sensitivity analysis suggests that no level of treatment results in more system-wide carbon than a completely untreated landscape, even in cases where treatment is presumed to be extraordinarily effective and efficient at minimizing wildfire effects. On the other hand, our exercises suggest that the carbon costs to reduce wildfire effects through fuel treatment appear relatively small.

Appendix A. Supplementary material

Supplementary material associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jenvman.2013.02.009.

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