Prescribed Fire As a Means of Reducing Forest Carbon Emissions in the Western United States

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Carbon sequestration by forested ecosystems offers a potential climate change mitigation benefit. However, wildfire has the potential to reverse this benefit. In the western United States, climate change and land management practices have led to increases in wildfire intensity and size. One potential means of reducing carbon emissions from wildfire is the use of prescribed burning, which consumes less biomass and therefore releases less carbon to the atmosphere. This study uses a regional fire emissions model to estimate the potential reduction in fire emissions when prescribed burning is applied in dry, temperate forested systems of the western U.S. Daily carbon dioxide (CO_2) fire emissions for 2001−2008 were calculated for the western U.S. for two cases: a default wildfire case and one in which prescribed burning was applied. Wide-scale prescribed fire application can reduce CO_2 fire emissions for the western U.S. by 18−25% in the western U.S., and by as much as 60% in specific forest systems. Although this work does not address important considerations such as the feasibility of implementing wide-scale prescribed fire management or the cumulative emissions from repeated prescribed burning, it does provide constraints on potential carbon emission reductions when prescribed burning is used.

1. Introduction

The potential climate change mitigation benefits of carbon sequestration by forested ecosystems have garnered both national and international attention. Recent legislation at state and regional levels in the United States has yielded nascent forest carbon accounting methodologies (e.g., Climate Action Reserve, Chicago Climate Exchange). These methodologies require that forest carbon offset projects sequester more carbon than business-as-usual (additionality) and that the carbon remain sequestered for some period of time (permanence). However, many of the world's terrestrial systems experience periodic fire events that emit a significant amount of carbon to the atmosphere in the form of carbon dioxide (CO_2), particles, and other trace gases (*1*), with climatic implications (*2*). Fire emissions are a critical component of the carbon cycle and need to be considered when evaluating regional sources and sinks of CO_2.

In the western United States, past land management activities that include grazing and fire suppression have altered the fire regimes of many dry forest types, resulting in a shift from frequent, low severity fire to infrequent, high severity fire (*3, 4*). Concurrent with management legacy influences, shifting climatic conditions, including earlier spring snowmelt, correlate with increased fire size and frequency (*5*), and current year climate, including low precipitation and high temperatures, correlates with area burned (*6*). This climate−fire relationship suggests that as the climate warms, fire will become even more prevalent in the western U.S (*7*). These two influences could potentially lead to greater releases of carbon to the atmosphere from fires.

Average annual fire emissions in the continental U.S. were estimated as 213 Tg CO_2 yr^{-1} from 2002−2006 (*1*). While relatively small when compared with average annual fossil fuel-based emissions in the U.S., the potential emissions contribution of wildfires is substantial and presents a risk to forest carbon offset projects (*8*). Fuel reduction treatments, such as mechanical thinning and prescribed burning, can be used to reduce CO_2 emissions from wildfires (*9, 10*), although both treatments have direct carbon emissions associated with implementation while reducing carbon stocks (*11*−*15*). The fraction of fuel combusted during a fire event tends to increase with increasing burn severity (*16*). Prescribed fires are typically less severe than wildfires since they are implemented when atmospheric conditions are stable and fuel moisture is high enough to maintain flame length, combustion, and spread rates within prescription, combusting less than 50% of the available fuel (*13, 17*). Additionally, prescribed fire conditions are such that overstory tree mortality rates are low (*18*), leaving much of the live-tree carbon pool intact. As a result, the amount of biomass combusted during a prescribed fire is less than what would occur during a wildfire (*19, 20*).

Although prescribed burning could potentially reduce the quantity of CO_2 emissions from fires in an ecosystem, there has not been a regional-scale examination of prescribed fire as compared to wildfire emissions of CO_2 to the atmosphere. Here, we use a continental-scale fire emissions model to investigate potential differences between wildfire and prescribed fire emissions in the western U.S. by using the land area burned by fire over the 2001−2008 period as the basis for comparison. While prescribed fires are typically applied at a frequency that is greater than wildfire occurrence at a specific location, quantifying the possible change in emissions when prescribed fire replaces wildfire will aid in determining the potential climate implications, allowing for further refinement of carbon accounting policy aimed at reducing atmospheric CO_2 concentrations.

2. Methods

2.1. Fire Emissions Model. Fire emissions were calculated using the framework described by Wiedinmyer et al. (*21*). Emissions were calculated using the following algorithm:

$$E_i = \sum A(x, t)^* B(x, t)^* FB^* ef_i \tag{1}$$

Where E_i is the emission flux of species i, $A(x,t)$ is the area burned at location x and time t, B is the biomass, or fuel, loading at location x and time t (mass per area), FB is the fraction of biomass burned, and ef_i is an emission factor for species i (mass species i emitted per biomass burned).

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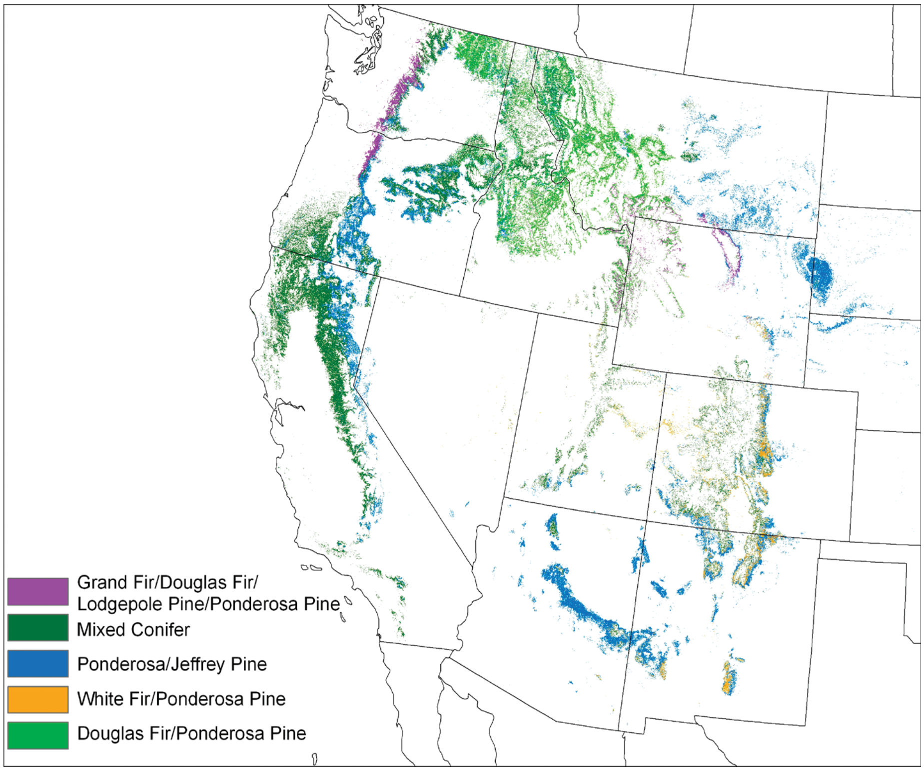

FIGURE 1. Mapping of forests in western U.S. identified by the LANDFIRE forest classes in which prescribed burning is suitable. The specific LANDFIRE classes have been lumped into five generic forest types shown here (see Table S1, Supporting Information).

Fire location and timing were determined with the Level 2 MODIS Fire and Thermal Anomalies (MCD14 ML) data product, Collection 5, Version 1 for the continental United States, Alaska, Hawaii, and Canada for years 2001−2008 (*22*−*24*). The MCD14 ML data used here are the official Level 2 MOD14/MYD14 data record from the NASA Land Processes Distributed Active Archive Center (LP-DAAC) and were provided for this study by the U.S. Forest Service Remote Sensing Applications Center (*25*). Ecosystem determination and forest cover were assigned with satellite mappings using methods described by Wiedinmyer et al. (*21*). The fraction of fuel burned is assigned to surface and woody fuels independently based on parametrizations described by Ito and Penner (*26*). Depending on the vegetation cover, up to 30% of the woody fuels and up to 98% of the surface fuels may burn.

Updates to the fire emissions model described by Wiedinmyer et al. (*21*) (version 1.0) include (a) removal of fires with confidence less than 20%, (b) removal of multiple detections of the same fire for each day (*27*), and (c) updated emission factors. Emission factors for CO_2 and CO were updated using recent data (*28, 29*). The updated fire emissions model used for this study can be referred to as version 2.0.

Daily estimates of fire emissions of CO_2 were calculated for 2001−2008 for eleven states in the western U.S. (Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming). The updates to the emissions model (version 2.0) lead to annual reductions in CO_2 emission estimates from fires in the western US of 40−56% compared to the results presented by Wiedinmyer and Neff (*1*) and fall more closely in line with other emission estimates. For example, Clinton et al. (*30*) estimate 2.7 million metric tons of CO_2 emitted from the Cedar Fire in California that occurred in October 2003; the model here estimates 1.3 million metric tons. For several fires in southern California in Fall 2003, the new emissions model estimates are within −60% to 35% of the estimates by Clinton et al. (*30*). The differences between the estimates of model version 1.0 and version 2.0 vary spatially and temporally. Due to the two satellite instruments and multiple daily overpasses, large wildfires common in the western U.S. can be detected more than once in the same day and often result in overlapping fire detections. The removal of multiple detections for individual fires in version 2.0 results in the largest reductions in emission estimates, particularly in active fire years. It should be noted, however, that the uncertainties associated with the emission estimates from fires remain quite large (estimated as a factor of 2) due to uncertainties associated with satellite fire detections, ecosystem and forest cover mappings, estimated burn area, fuel loadings, and emissions factors. A detailed discussion of these uncertainties is provided by Wiedinmyer et al. (*21*).

2.2. Prescribed Burning Emission Estimation. To simulate the replacement of wildfires with prescribed burning in suitable forests of the western U.S., several steps were taken. First, only western forests that historically had fairly frequent fire return intervals and either low or mixed severity effects (*31*−*33*) were judged amenable for prescribed burning. These forest types are typically targeted for fuels reduction treatments because a legacy of fire suppression has resulted in increased fuel accumulation and a commensurate increase in high severity fire activity. These forest types were spatially mapped using the LANDFIRE existing vegetation type data product (www.landfire.gov). The LANDFIRE database provides landscape-level land cover and land use information for the U.S. and identifies 466 different land use and land cover classifications for the western U.S. A total of 19 LANDFIRE forest classifications in the western U.S. have historic fire regimes of either low or mixed severity, and prescribed burning was assumed to be appropriate only in these classes (Figure 1, Table S1 in the Supporting Information). To facilitate the emissions modeling, each of these LANDFIRE classes was assigned to one of five generic forest types (Table S1 in the Supporting Information). For each of these forest types, the fraction of the fuel assumed to burn under prescribed burning practices was assigned based on

TABLE 1. Summary of Estimated State-Level Fire Emissions from the Default and the Prescribed Burning Simulations[a]

state	% of total emissions from LANDFIRE classes (*Table S1*)	default μ ($TgCO_2\ yr^{-1}$)	default σ	prescribed fire μ ($TgCO_2\ yr^{-1}$)	prescribed fire σ	% change	default μ ($TgCO_2\ yr^{-1}$)	default σ	prescribed fire μ ($TgCO_2\ yr^{-1}$)	prescribed fire σ	% change
Arizona	44	**4.1**	**1.5**	**3.1**	**1.2**	**−23**	1.8	0.7	0.9	0.3	−52
California	36	**18**	**16**	**14**	**11**	**−19**	6.3	7.6	2.4	2.7	−60
Colorado	33	**1.4**	**1.4**	**1.1**	**0.9**	**−16**	0.5	0.7	0.2	0.2	−60
Idaho	35	**12**	**12**	**9.1**	**9**	**−21**	4.0	4.4	1.5	1.7	−62
Montana	36	**8.1**	**8.4**	**6.2**	**6.6**	**−24**	2.9	2.8	1.1	1.0	−63
New Mexico	1	**1.0**	**0.7**	**1.0**	**0.7**	**−1**	0.0	0.0	0.0	0.0	−37
Nevada	49	**2**	**1.1**	**1.5**	**0.8**	**−26**	1.0	0.6	0.4	0.3	−57
Oregon	32	**9.9**	**7.4**	**8.1**	**5.7**	**−16**	3.1	2.8	1.3	1.1	−56
Utah	13	**1.4**	**0.6**	**1.3**	**0.5**	**−7**	0.2	0.1	0.1	0.0	−54
Washington	39	**5.9**	**4.6**	**4.4**	**3.4**	**−24**	2.3	1.9	0.9	0.7	−62
Wyoming	21	**1.4**	**0.8**	**1.2**	**0.7**	**−14**	0.3	0.2	0.1	0.1	−57

[a] All values have been averaged for 2001−2008. The columns which display bold data are the emission estimates for all fires simulated; the last columns are the emissions estimates from forest types in which prescribed burning was applied.

the results of pre- and postprescribed fire fuel consumption studies (*34, 35*) (Table S2 in the Supporting Information).

To model the replacement of wildfire with prescribed burning, the fractions of biomass burned (FB in eq 1) for the fires located in the five forest types were assigned new values (Table S2 in the Supporting Information). The fraction of fuel consumed in prescribed fires was applied only to the surface fuel fraction (including herbaceous, fine, and coarse fuels) of the total fuel loading in the model (Table 1 of ref (*21*)); no live or standing dead trees are assumed to burn in prescribed fires. For this preliminary sensitivity analysis, all fires in the five forest types were assumed to be prescribed and were assigned prescribed burning FB values in the model code. Emission factors used for the prescribed fire scenario were the same as the default model simulation. Thus, this sensitivity test provides an upper limit to the amount of emissions that could be altered using this practice. Additionally, fire frequency and timing remained the same for both the initial estimates and the sensitivity scenario (i.e., the MODIS satellite fire detections were used in both cases to identify fire location and timing). In practice, we would expect changes in the timing and seasonality, with prescribed fires restricted to those periods when fire crews are available, and when fuel moisture and atmospheric conditions are within prescription. Using this new, prescribed burning scenario, daily fire emissions were calculated for the western U.S. for 2001−2008 for comparison to version 2.0 of the default wildfire model simulation presented in Wiedinmyer et al. (*21*).

3. Results

Modeled annual CO_2 emissions from fire for the eleven western states range from 22 Tg CO_2 (2001) to 103 Tg CO_2 (2007) (Supporting Information, Figure S1). Annually averaged state-wide fire emissions range from 1−18 $TgCO_2\ yr^{-1}$ from 2001−2008 (Table 1), with the highest annual fire emissions from California, Idaho, Oregon, and Montana. Because the emissions model is driven solely by satellite fire detections, these estimates include emissions from all fires (e.g., agricultural, forest, grassland, etc.). Given the episodic nature of fire occurrences, the interannual variability of the emissions is substantial (e.g., Table 1, Supporting InformationTable S3); annual statewide fire emissions can vary by as much as factor of 20 (Idaho). For example, Figure 2 shows the annual estimated CO_2 emissions from fires in California, Idaho, Montana, and Oregon from 2001−2008, highlighting the interannual variability in the estimated fire emissions, as well as the spatial variability from state to state.

Fires located in forest types that historically experienced frequent, low- and mixed-severity fire regimes (Figure 1, LANDFIRE Classes in Table S1 of the Supporting Information,) contributed an average of 35% of annual CO_2 emissions for the western U.S., and as much as 49% of total state-level fire emissions (Table 1; Supporting InformationFigure S1). Replacing wildfire emissions with prescribed fire emissions in these forest types reduced simulated annual statewide emissions by an average of 1−26%, and forest type-specific emissions by 37−63% (Table 1). The results compare reasonably with other model-based comparisons. For example, Hurteau and North (2009) show that carbon emissions in a prescribed burn were 69% less than a wildfire in a mixed-conifer forest in the Sierra Nevada. A report to the Western Regional Air Partnership (*36*) assigned emissions factors that are 74% (carbon monoxide) and 67% (fine particulate matter) lower for prescribed burns than for wildfires.

New Mexico showed the largest overall percentage reduction in CO_2 emissions when prescribed burning was applied (35% in 2002); however, the magnitude of emissions from this state is quite small compared to emissions from other western states. In states with larger annual emissions from fires, reductions as large as 16 Tg CO_2 (California in 2008) were simulated (Table 2). Figure 3 shows the annual CO_2 emissions for all fires (i.e., agriculture, grass, forest) in 2006 for the eleven western states for both the default model simulation and for the one in which prescribed burning was applied. States with the highest CO_2 fire emissions have the largest reductions in CO_2 when prescribed fire is substituted for wildfire. Table 2 gives the reductions in annual CO_2 emissions from fires for each state from 2001−2008 when prescribed burning is applied to all fires located within the LANDFIRE classes (defined in Table S1 of the Supporting Information). The reductions are substantial, and also show in which states the use of prescribed fire would have the greatest benefit.

Of the five generic forest types assigned prescribed burning (Figure 1, Table S1 of the Supporting Information), fire emissions from the mixed-conifer forest type are the greatest, followed by ponderosa/Jeffrey pine forests and Douglas-fir/ponderosa pine forests (See Supporting Information, Table S4). Average annual emissions from the other two forests types were small in comparison. Average annual emission reductions from prescribed burning in the five forest types ranged from 52−68%. This varied by year and by state; however, emission reductions were found to be on the order of 50−60%, as expected from the assigned changes in respective fraction of biomass burned applied in the sensitivity model simulation. For example,

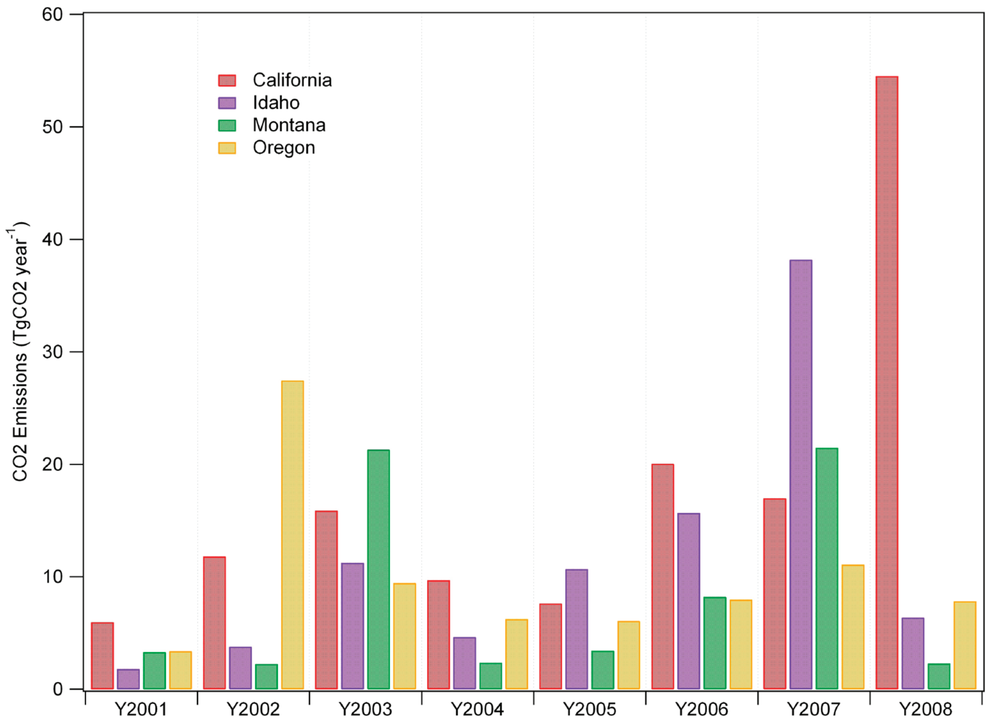

FIGURE 2. Annual CO_2 emissions from fires in California, Idaho, Montana, and Oregon. CO_2 emissions can vary as much as a factor of 10−20 from year to year.

TABLE 2. Annual Reductions in CO_2 Emissions (Tg CO_2 yr^{-1}) and Percent Reductions (in parentheses) from All Fires When Prescribed Burning Is Applied

year	Arizona	California	Colorado	Idaho	Montana	Nevada	New Mexico	Oregon	Utah	Washington	Wyoming
2001	0.4 (−29)	1.2 (−20)	0.1 (−12)	0.3 (−16)	0.7 (−22)	0.01 (−1)	0.12 (−20)	0.5 (−13)	0.04 (−6)	0.7 (−23)	0.1 (−16)
2002	1.7 (−29)	1.9 (−16)	1.4 (−29)	0.8 (−22)	0.6 (−26)	0.0 (0)	0.6 (−35)	5.9 (−21)	0.2 (−10)	0.8 (−23)	0.2 (−15)
2003	1.2 (−25)	2.0 (−12)	0.2 (−15)	2.2 (−20)	4.3 (−20)	0.0 (0)	1.2 (−28)	1.7 (−18)	0.1 (−7)	1.7 (−23)	0.2 (−13)
2004	0.8 (−16)	1.2 (−12)	0.2 (−15)	1.0 (−21)	0.7 (−31)	0.02 (−6)	0.6 (−28)	1.0 (−15)	0.1 (−7)	1.7 (−29)	0.1 (−16)
2005	0.7 (−14)	1.5 (−19)	0.2 (−17)	2.2 (−20)	0.9 (−25)	0.0 (0)	0.7 (−30)	0.8 (−13)	0.1 (−7)	0.6 (−20)	0.1 (−23)
2006	0.8 (−25)	5.5 (−28)	0.1 (−17)	3.4 (−22)	2.2 (−26)	0.0 (0)	0.6 (−25)	1.1 (−14)	0.1 (−6)	4.5 (−27)	0.1 (−4)
2007	0.9 (−27)	2.3 (−14)	0.1 (−10)	8.7 (−23)	5.0 (−23)	0.01 (−1)	0.3 (−24)	2.0 (−18)	0.1 (−5)	1.0 (−24)	0.2 (−11)
2008	0.8 (−24)	15.7 (−29)	0.2 (−15)	1.3 (−21)	0.5 (−20)	0.02 (−2)	0.3 (−20)	1.3 (−16)	0.1 (−7)	0.6 (−21)	0.3 (−15)
Average	0.9 (−23)	3.9 (−19)	0.3 (−16)	2.5 (−21)	1.9 (−24)	0.0 (−1)	0.6 (−20)	1.8 (−16)	0.1 (−7)	1.5 (−24)	0.2 (−14)
Maximum	1.7 (−29)	15.7 (−29)	1.4 (−29)	8.7 (−23)	5.0 (−31)	0.02 (−6)	1.2 (−35)	5.9 (−21)	0.2 (10)	4.5 (−29)	0.3 (−23)
Minimum	0.4 (−14)	1.2 (−12)	0.1 (−10)	0.3 (−16)	0.5 (−20)	0.0 (0)	0.1 (−20)	0.5 (−13)	0.04 (−5)	0.6 (−20)	0.1 (−4)

in Oregon, mixed-conifer and ponderosa/Jeffrey pine forests are the dominant source of fire emissions. However, emissions from grand fir/Douglas-fir/lodgepole pine/ponderosa pine forest can also contribute significantly (e.g., 2003 and 2007) (See Supporting Information, Table S4). Reductions in CO_2 emissions from mixed-conifer forests can vary as much as 7% in Oregon (57−64%). Figure 4 shows the estimated annual reductions in fire emissions from mixed-conifer forests for California, Oregon, Washington, and Idaho (See Supporting Information, Table S4 and Figures S2−5 for reductions in other forest types).

Across the western U.S., the largest emissions typically occur during the peak of the wildfire season (August), with elevated emissions from July though October (Figure 5). The monthly average CO_2 emissions reduction is 17% (5−24%). For all of the western states, the largest reductions occur in the period from August through November.

Given the questionable feasibility of large-scale prescribed burning, implementation may only be practical in lands managed by the federal government, including (*but not limited to*) the Bureau of Land Management (BLM), the U.S. Forest Service (USFS), the National Parks Service (NPS), and the Department of Defense (DoD). From 2001−2008 in the western U.S., an average of 71% (57−78%) of the estimated fire emissions came from fires located on federally controlled lands. Specifically, fires occurring on lands controlled by the USFS average 60% of all annual fire emissions in the western U.S.; followed by the BLM (6%) and the NPS (4%). A majority of the forests to which prescribed burning was applied are located within federally controlled lands; emissions from these forests contributed 82% of the wildfire emissions from the default model. In 2008 in California, 84% of the estimated emissions occurred on Federal Lands (78% on USFS lands); however, in 2004 in California, only 49% of the estimated emissions occurred on Federal Lands. The results show that federal agencies manage much of the dry forest types that would benefit from prescribed burning.

4. Discussion

The climate change mitigation potential of forests represents one of the stabilization wedges identified by Pacala and Socolow (*37*) as an existing technology that can be utilized to stabilize atmospheric greenhouse gas concentrations. In the tropics, reducing deforestation represents a clear path toward maintaining the forest carbon sink in equatorial

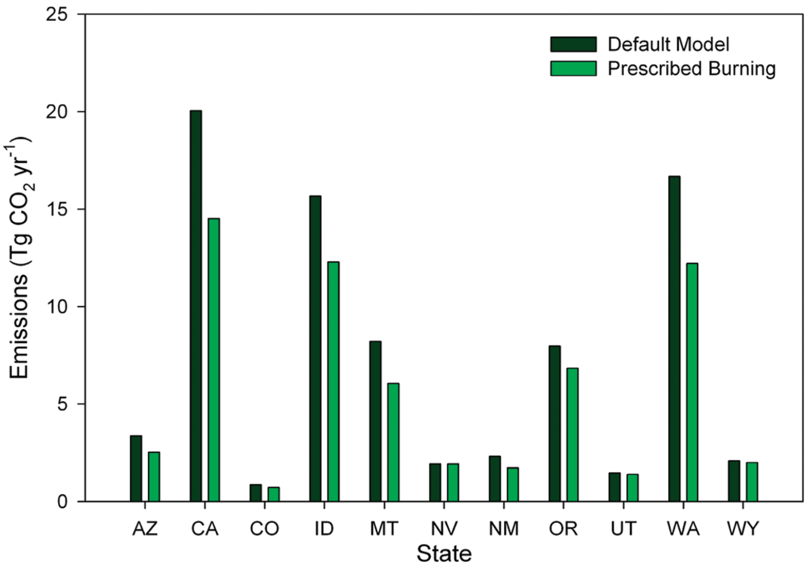

FIGURE 3. Annual estimates (for 2006) of CO_2 emissions from fires for the default model simulation and the one in which prescribed burning was applied.

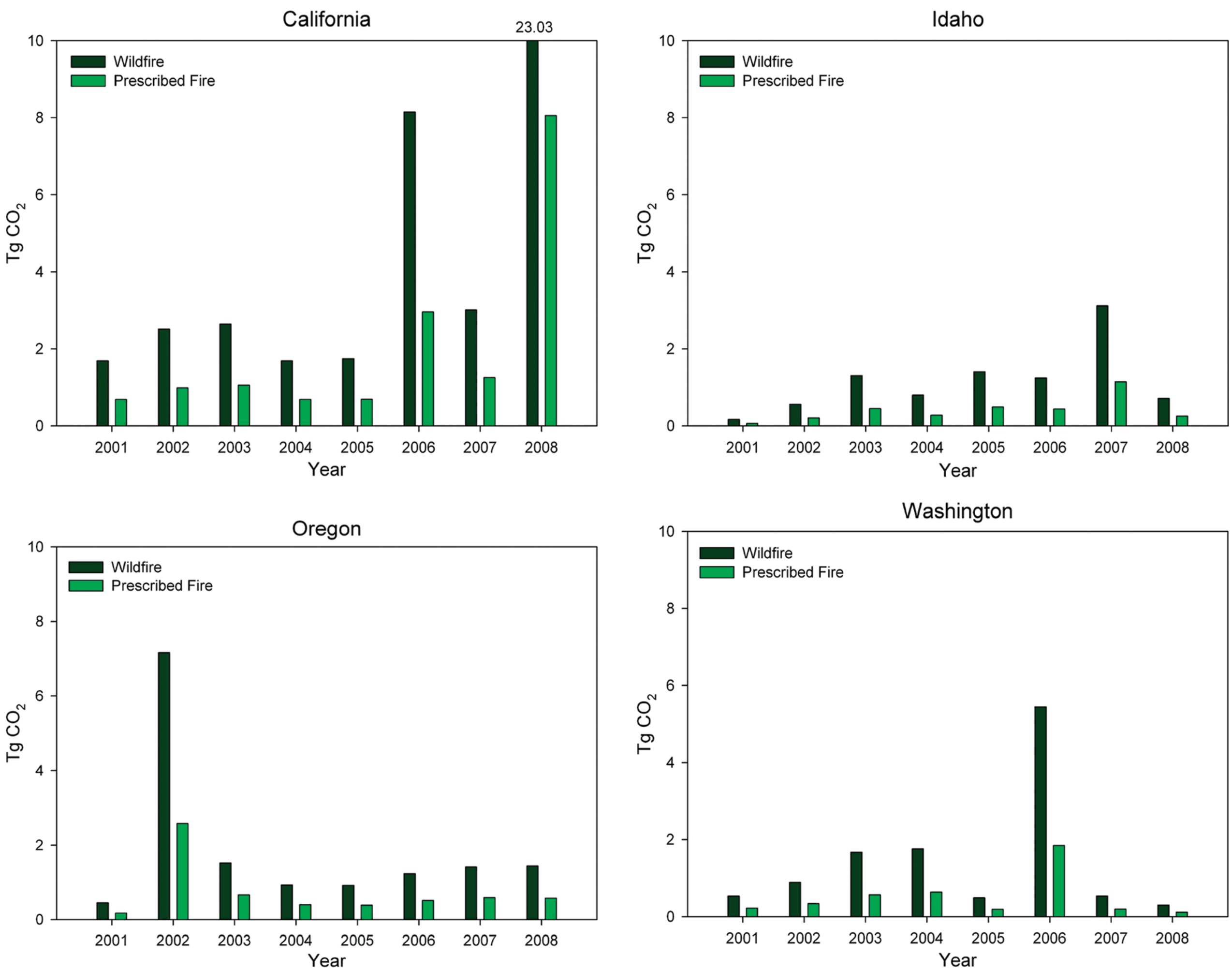

FIGURE 4. CO_2 emission estimates for 2001−2008 from fires in Mixed Conifer Forests in California, Oregon, Washington, and Idaho for the default simulation and when prescribed burns are applied.

regions (*38*). However, in temperate forests the appropriate management action to maximize the climate change mitigation potential of a given tract of forest may be less obvious. Currently, forests in the U.S. sequester approximately 10% of the annual U.S. anthropogenic emissions (*39*). While carbon sequestration by forests provides an important ecosystem service, relying on the continued strength of this sink is tenuous at best given the influence of changing climatic conditions on these ecosystems and the projected decline in the sink strength even with continued suppression (*7, 40, 41*).

In the dry, fire prone forests of the western U.S., wildfire size and severity have been increasing as a result of changing

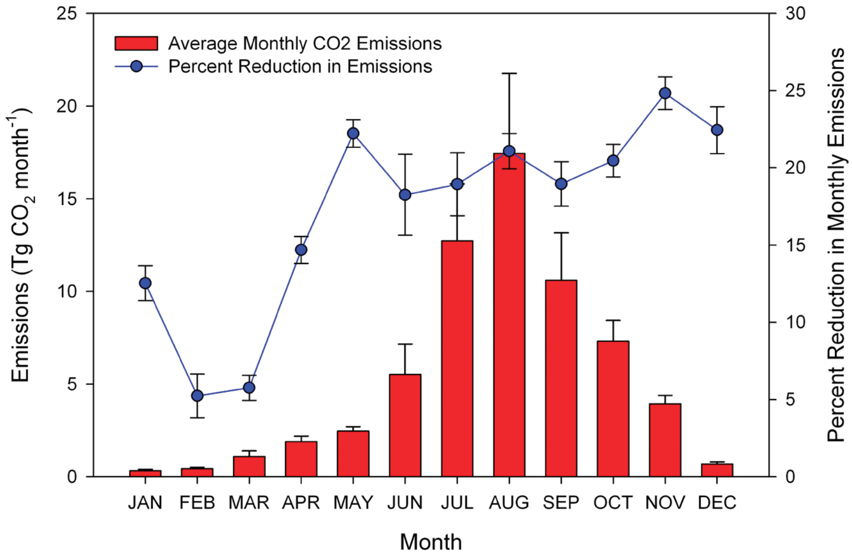

FIGURE 5. Monthly averaged (2001−2008) estimated CO_2 fire emissions for all eleven western states (Red). Average percent reduction in CO_2 emissions when prescribed burning is applied in applicable forest types (blue). Error bars represent the standard error of the monthly estimates.

climatic conditions and past management activities (*3, 5*). Wildfire, in addition to being an impediment to meeting the permanence requirement for generating forest carbon offsets, is also a significant source of carbon emissions (*1, 42*). Reducing the risk of high severity fire in the dry forest types of the western U.S. requires a reduction in forest carbon stocks (*12, 15*). Despite these reductions, carbon continues to accumulate as a result of forest growth following treatment implementation (*14*).

The results of this study suggest that prescribed burning could reduce CO_2 and other emissions from fires in dry forest types by 52−68%. This equates to overall fire emission reduction in the western U.S. of 18−25%, and as much as 35% at the state level. This result is similar to that of Narayan et al. (*10*), who suggest that in areas of high wildfire occurrence in Europe, CO_2 emissions could potentially be reduced by as much as 50% when prescribed burning replaces wildfire. However, given the relatively short temporal scale of the MODIS fire and thermal anomalies data product, the total potential emissions reduction should be viewed with the caveat that large fire events, such as the Yellowstone fires in 1988, would increase the total wildfire emissions and decrease the total emissions reduction from prescribed fire. This is due to the fact that the Yellowstone fires burned within the historic range of variability (*43*) for this system and regular prescribed fire would be an inappropriate management technique.

Prescribed burning is a potential way to manage CO_2 fluxes from forests in regions with high wildfire activity such as the western U.S. Managing forest fuels with prescribed fire requires repeated application at a frequency that is appropriate to meet management goals, and quantifying the carbon costs would require an assessment of the cumulative emissions coupled with quantification of sequestration by the remaining trees. In cases where high severity fire can transition the forest from a sink to a source for an extended period of time (e.g., ref (*44*)), cumulative prescribed fire emissions are likely to be lower than wildfire emissions coupled with lost sink strength. However, in systems where tree regrowth is faster, repeated prescribed burning may have a higher carbon cost than a one-time wildfire event. The purpose of this work was to set an upper bound for the potential reduction in CO_2 emissions that could be achieved when prescribed fire replaces wildfire. These findings indicate that prescribed burning emissions on a per fire basis are considerably lower than emissions from wildfire. Furthermore, live tree mortality rates from prescribed burning are typically lower than from wildfire (*13*), and the remaining live trees continue to sequester carbon. While prescribed burning does not eliminate the occurrence of wildfire in these systems, there is evidence that treating fuels limits the severity of wildfire when it does occur because of limited fuel availability (*45, 46*). This study is a first step in evaluating the potential of using prescribed fire to reduce wildfire emissions and increase the long-term stability of forest carbon. These results can support the determination of regional C fluxes within the U.S. and help constrain the potential emissions reductions that can be achieved through prescribed burning. This study does not take into account important factors, such as regional differences in prescribed fire emissions factors, combustion efficiencies, timing of prescribed burning practices, feasibility, mean fire return intervals, and air quality impacts. However, future work will include the impacts of these important considerations.

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Supporting Information Available

Descriptions of forest type grouping, prescribed fire biomass consumption parameters, and state and forest type emission values. This information is available free of charge via the Internet at http://pubs.acs.org/.

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