Forest Biomass and Tree Planting for Fossil Fuel Offsets in the Colorado Front Range

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Abstract—This study estimates the amount of carbon available for removal in fuel reduction and reforestation treatments in montane forests of the Colorado Front Range based on site productivity, pre-treatment basal area, and planting density. Thinning dense stands will yield the greatest offsets for biomass fuel. However, this will also yield the greatest carbon losses, if the removals remain on site to decompose. Stands that regrow the biomass removed will recover the carbon. However, if these treatments are maintained at low basal areas, then the treatments may permanently convert a large quantity of carbon from the forest to the atmosphere.

Keywords: ponderosa pine, carbon, wildfire risk, FVS, biomass

Introduction

Over the past century, the exclusion of wildfires in ponderosa pine/Douglas-fir (*Pinus ponderosa* / *Pseudotsuga menziesii*) forests has increased tree density in most landscapes. While this increase in tree density serves as a carbon sink, these same areas are at higher risk for a high severity fire, which could lead to a substantial initial release of carbon if trees are killed and the fire consumes the forest floor, foliage, and wood (Hurteau and others 2008; Hurteau and North 2009). Several recent high severity wildfires in the ponderosa pine/Douglas-fir forests of the Colorado Front Range have converted dense forests into large areas with no living trees and minimal ability to regenerate (Romme and others 2003). Since these areas have little to no regeneration, natural forest regrowth will not replace the carbon lost to combustion and decomposition and the area will become a carbon source (Dore and others 2008; Kashian and others 2006) for the foreseeable future. These fires have prompted the implementation of fuel reduction treatments intended to reduce crown fire risk. These treatments often involve removing small-diameter, non-merchantable trees that established over the past century. Since the biomass removed is non-merchantable, it is typically piled and burned or masticated, which moves carbon dioxide (CO_2) stored in the forest to the atmosphere. Furthermore, the lack of removable merchantable material makes these treatments costly.

The increase in atmospheric CO_2 and its role in global climate change have encouraged the search for ways to reduce or offset greenhouse-gas emissions. Emissions cap-and-trade programs or voluntary carbon trading programs can reduce CO_2 input to the atmosphere by creating a market aimed at decreasing fossil fuel emissions (Ellerman and others 1998; Petty and Ball 2001; Zhang and Folmer 1995). Carbon credit trading allows industries to buy credits from

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industries or entities that have reduced their emissions. Companies can choose to invest in reforestation projects that remove CO_2 from the atmosphere, or to use alternative energy sources for fossil fuels in heat and power generation. The large area currently storing carbon but in need of thinning for fire hazard reduction could benefit from these programs.

Biomass harvested from fuel reduction treatments could substitute for fossil fuels currently used for heat and power generation. The credits generated by the use of the biomass fuel could help compensate for the costs of the management activities, depending on the price of the credits. Also, planting trees in burned areas can help restore forests and promote carbon sequestration. While the initial harvests to reduce crown fire risk may result in immediate CO_2 offsets if used for biomass energy, the maintenance of low forest density to maintain low crown fire risk will reduce potential carbon stored on the landscape. This study estimates the amount of carbon available now for removal in fuel reduction and reforestation treatments in the ponderosa pine/Douglas-fir forests of the Colorado Front Range based on site productivity, pre-treatment basal area, and planting density. We also estimate the carbon storage potential of tree planting on areas not expected to regenerate naturally. Finally, we estimate the potential carbon offsets and associated crown fire risk for different management scenarios.

Methods

Study Area

Our study area was located within the Pike and San Isabel National Forest (PSINF) in Colorado, southwest of Denver (fig. 1). Tree species are ponderosa pine, Douglas-fir, quaking aspen (*Populus tremuloides* Michx.), lodgepole pine (*Pinus contorta* Douglas ex Louden), Engelmann Spruce (*Picea engelmannii* Parry ex Engelm.), and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.). Site index on the PSINF varies from 30 to 80 ft (index age of 100 years).

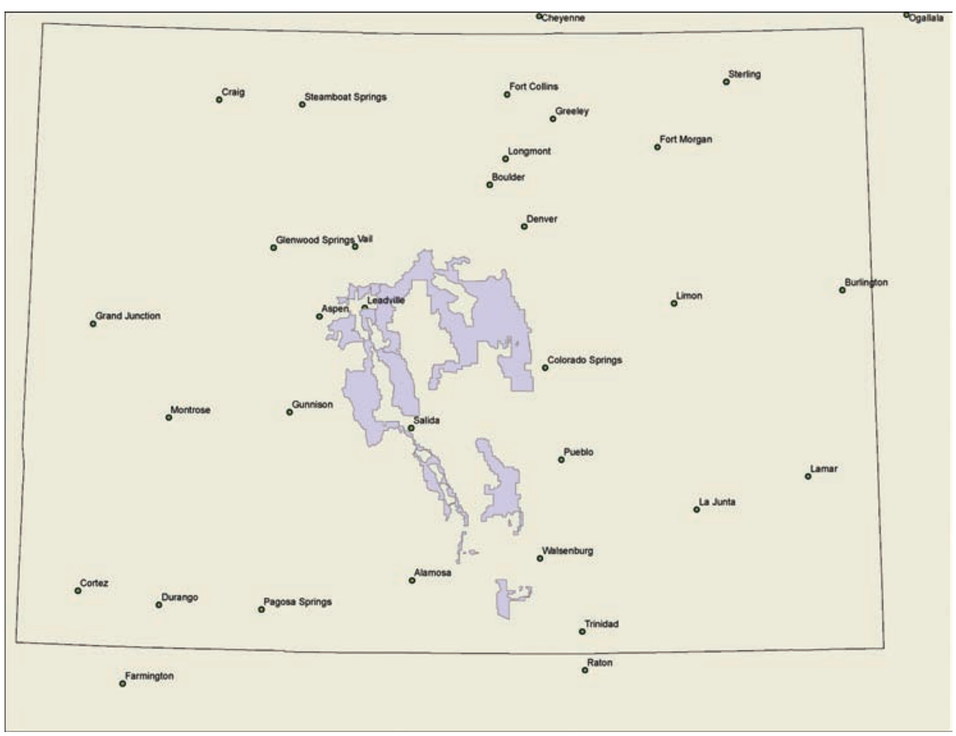

Figure 1—Location of the Pike-San Isabel National Forest (shaded) within the state of Colorado.

We studied the dry ponderosa pine/Douglas-fir forest because this is the forest type that has experienced severe wildfires and would likely be the area treated for fuel reduction. The dry ponderosa pine/Douglas-fir forests of the PSINF are found from 6,500 to 9,000 ft in elevation. Ponderosa pine dominates the south and west facing slopes and the Douglas-fir dominates the northern slopes. The understories are typically grassy, shrubby, or both. Soils are gravelly coarse sandy loams derived from weathered Pikes Peak granite (Moore 1992).

Overview

We modeled two scenarios (Fuel Reduction Treatment and Reforestation) to develop estimates for the amount of carbon that is currently and potentially available. We calibrated the Forest Vegetation Simulator (FVS) forest growth model to match growth conditions found on the PSINF and modeled carbon accumulation for different management and site index scenarios. Specifically, carbon accumulation was estimated by 1) using USDA Forest Service inventory data to determine the range of site indices and actual forest growth for areas within the PSINF either in need of fuels reduction or in areas burned in the Hayman wildfire, 2) calibrating FVS to match actual forest growth for the different site index values, 3) using the FVS model to model organic material accumulation for a range of site index values, and 4) applying literature-based values to estimate carbon content of biomass and carbon dioxide equivalent in metric tons per acre (MT/ac). We included belowground biomass and organic material accumulation (forest floor) in our carbon estimates.

The Forest Vegetation Simulator

The Forest Vegetation Simulator (Dixon 2002) is an individual tree and stand level growth and yield model that is based on the Prognosis model (Stage 1973). The Extensions to Prognosis began in 1978, and GENGYM (Edminster and others 1991), today known as the "Central Rockies Variant," was developed in 1991. Like the Prognosis model, the Central Rockies Variant is a set of allometric equations that defines growth rates for tree species in New Mexico, Arizona, Colorado, and South Dakota. This variant is broken into five sub-variants. The sub-variant specific to the PSINF region was used to generate the information in this study.

Scenarios

Current management guidelines in the PSINF for fuels reduction and forest restoration involve reducing standing forest biomass to a target basal area of 40 to 60 ft^2/ac. This guideline is based on research done by Merrill Kaufmann and others (Kaufmann and others 2000; Kaufmann and others 2001; Romme and others 2003) in the area surrounding Cheeseman Reservoir, Deckers, Colorado.

Fuel reduction treatment—We downloaded inventory data from the PSINF Resource Information System (RIS) database. The RIS database was queried for stand identification numbers of suitable ponderosa pine/Douglas-fir sites. Stands were sorted into 4 site index groups (45, 55, 65, and 75). Using FSVeg, specific stand exams were downloaded and entered into the FVS program.

We used FVS to grow each site index group until a specific management criterion was met and then had the model simulate thinning. For each of these groups, the FVS model was set up to grow to 6 different basal areas (90, 100, 110, 120, 130, and 140 ft^2/ac). Each basal area class was thinned to three post-treatment basal area targets (40, 50 and 60 ft^2/ac). These values encompass the range of possible management targets that a manager may chose, given the flexibility in potential management practices. The *ThinBBA* keyword (thin from below to a specific basal area target) was used in the FVS model to allow the model stand to grow to and be thinned to a specified basal area target.

We simulated two additional scenarios to assess the potential carbon offsets and associated fire risk for stands managed to maintain fuel treatment effectiveness. For both scenarios, we chose to model the stands with a site index of 45. In the first scenario, the initial basal area was 100 ft^2/ac, and then it was thinned from below to 50 ft^2/ac and allowed to grow back to 100 ft^2/ac and thinned again to 50 ft^2/ac. In the second scenario, the initial basal area was 160 ft^2/ac, and then it was thinned from below to 50 ft^2/ac and only allowed to grow to 100 ft^2/ac and thinned again to 50 ft^2/ac. In both scenarios, the fire risk associated with the management regime was assessed with the fire and fuels extension (FFE) to FVS. FFE provides estimates of the torching and crowning index based on canopy base height, canopy bulk density, and an estimated fuel model. The torching index is the windspeed at 20 ft required to initiate a passive crown fire. The crowning index is the windspeed at 20 ft required to sustain an active crown fire (Scott and Reinhardt 2001). These scenarios were simulated for a 200 year period.

Reforestation—We selected ponderosa pine stands from the post-Hayman fire reforestation needs GIS coverage map. The polygons identified areas within the Hayman wildfire that had no living trees and lacked a seed source. These polygons had records that include stand inventory codes that allow the user to download stand exams from the PSINF database using the Forest Service's FSVeg network application.

The reforestation scenario used a matrix of site indices and planting densities to compare the differences in carbon storage for these scenarios. Site index values were taken from PSINF stand inventories completed between 1978 and 2000. Site index values ranged from 30 to 58, with only a few stands having a site index >55. We modeled growth for site index values of 35 to 55 in increments of 5. We modeled *surviving* tree density from a planting density of 100, 200, and 300 trees per acre for each site index value. The "surviving planting number" is the number of seedlings per acre remaining on a site after any post-planting mortality. These surviving planting densities were chosen to represent the tradeoff between high density with rapid carbon accumulation and frequent thinning to reduce fire risk, to low density with slow carbon accumulation but few necessary thinnings. These scenarios were simulated for one harvest cycle (typically 80 to 100 years).

Similar to the 'biofuels' simulations, two additional scenarios were simulated to assess the potential carbon offsets and associated fire risk for reforested stands that would be managed to maintain fuel treatment effectiveness. For both scenarios, we chose to model the stands with a site index of 45 and initial planting density of 450 trees per acre. In the first scenario, we allowed the stand to grow with no thinning activities for 400 years. In the second scenario, we allowed the stand to grow to 100 ft^2/ac and thinned from below to 50 ft^2/ac. We repeated this management regime for 400 years. In both scenarios, the fire risk associated with the management regime was assessed with the fire and fuels extension (FFE) to FVS.

Calculating Carbon Stores

To determine the amount of carbon stored for each scenario, we used the 'FuelOut' keyword in FVS to request a report of biomass in all forest carbon pools. Forest floor (sum of surface litter, surface duff, and surface wood—mostly litter and duff) and total standing biomass (sum of standing live wood, large roots, standing snags, and foliage) were calculated and summed as the total biomass accumulation in a forest stand. Although FVS now has the ability to calculate forest carbon, when the simulations were run, the extension was still in development. We estimated the belowground biomass (large roots) as 25 percent of the aboveground biomass (Jackson and Chittenden 1981). We assumed that biomass was 50 percent carbon (Schlesinger 1997). Carbon trading uses CO_2 instead of carbon, so we multiplied total carbon by 3.67, the ratio of the molecular weights of CO_2 to carbon (Chicago Climate Exchange, Inc. 2004; US Department of Energy 2007). We report our values in metric tons CO_2 equivalent per acre (MT CO_2/ac)

Results

Fuel Reduction Treatment: Initial CO_2 offsets

Biomass available from fire hazard reduction activities in ponderosa pine/Douglas-fir forests of the PSINF varied by pre-treatment basal area, site index, and the post-treatment basal area. Dense stands will yield the most biomass and offsets, especially if they are thinned to the lower target basal area of 40 ft^2/ac (table 1). For example, stands with a site index of 45 and pre-treatment basal areas between 90 and 140 ft^2/ac will generate fossil fuel offsets between 18.6 to 43.6 MT CO_2/ac if thinned to a target basal area of 40 ft^2/ac (table 1). If these same stands were thinned to a target basal area of 60 ft^2/ac, they will generate fossil fuel offsets between 9.0 to 32.5 MT CO_2/ac (table 1). If these stands had a site index of 75, they would generate fossil fuel offsets between 22 to 55.3 CO_2 MT/ac if thinned to a target basal area of 40 ft^2/ac and 10.5 to 41.3 CO_2 MT/ac if thinned to a target basal area of 60 ft^2/ac (table 1).

Maintenance of Fuel Reduction Treatment: Future CO_2 Offsets and Fire Risk

Maintaining ponderosa pine/Douglas-fir forests between 50 and 100 ft^2/ac reduces fire risk by increasing the windspeed required to sustain an active crown fire. Before the initial harvest, the 100 ft^2/ac and the 160 ft^2/ac stands had low crowning indices, 26 (fig. 2) and 13 (fig. 3) mph, respectively. After the initial entry, crowning indices increased substantially (figs. 2 and 3). As the stands accu-

Table 1—Average (± standard error, in parentheses) metric tons of CO_2 equivalent per acre available for immediate biomass removal for different site productivities, pre-treatment basal area[a], and residual post-treatment basal area of ponderosa pine/Douglas-fir stands in need of fuel reduction treatments on the Pike and San Isabel National Forest, Colorado.

Pre-trt BA [a]		Site index = 45				Site index = 55				Site index = 65				Site index = 75		
	Target basal area (ft^2/ac)															
	0	40	50	60	0	40	50	60	0	40	50	60	0	40	50	60
ft^2/ac	----Metric tons of CO_2 equivalent per acre (± standard error)----															
90	39.1 (1.2)	18.6 (0.77)	13.7 (0.57)	9.0 (0.54)	42.4 (1.2)	20.1 (0.75)	14.8 (0.70)	9.9 (0.59)	47.5 (2.0)	22.8 (1.12)	17.2 (1.04)	10.9 (0.65)	46.5 (1.7)	22.0 (1.18)	15.7 (0.96)	10.5 (0.87)
100	45.3 (1.4)	23.9 (0.90)	19.9 (0.79)	13.9 (0.63)	48.0 (1.2)	25.1 (0.81)	19.9 (0.81)	14.7 (0.70)	52.1 (1.7)	27.4 (1.10)	21.4 (1.03)	16.2 (0.81)	53.5 (1.9)	28.4 (1.14)	21.7 (0.94)	16.2 (0.75)
110	50.4 (1.6)	28.9 (1.07)	23.6 (0.97)	18.3 (0.86)	52.9 (1.2)	30.0 (0.87)	24.4 (0.84)	19.1 (0.77)	57.4 (1.7)	32.7 (1.23)	26.3 (1.10)	20.9 (0.91)	60.1 (2.1)	34.1 (1.37)	27.8 (1.25)	21.4 (1.00)
120	55.5 (1.8)	33.8 (1.22)	28.4 (1.11)	23.1 (0.99)	59.1 (1.2)	35.6 (0.91)	29.7 (0.86)	24.4 (0.84)	63.9 (1.8)	38.6 (1.29)	32.1 (1.20)	26.9 (0.96)	66.4 (3.0)	40.1 (2.07)	33.8 (1.87)	27.2 (1.64)
130	60.0 (1.8)	38.4 (1.36)	32.8 (1.22)	27.5 (1.22)	63.8 (1.4)	40.4 (1.05)	34.4 (0.98)	28.7 (0.88)	71.0 (2.3)	45.4 (1.75)	38.2 (1.28)	32.2 (1.25)	75.3 (3.3)	48.1 (2.33)	41.2 (2.13)	34.5 (1.96)
140	65.6 (2.1)	43.6 (1.63)	38.0 (1.50)	32.5 (1.43)	70.4 (1.5)	46.8 (1.12)	40.4 (1.02)	34.7 (0.94)	77.9 (2.2)	51.7 (1.63)	45.2 (1.46)	38.5 (1.32)	83.0 (3.8)	55.3 (2.74)	48.1 (2.6)	41.3 (2.34)

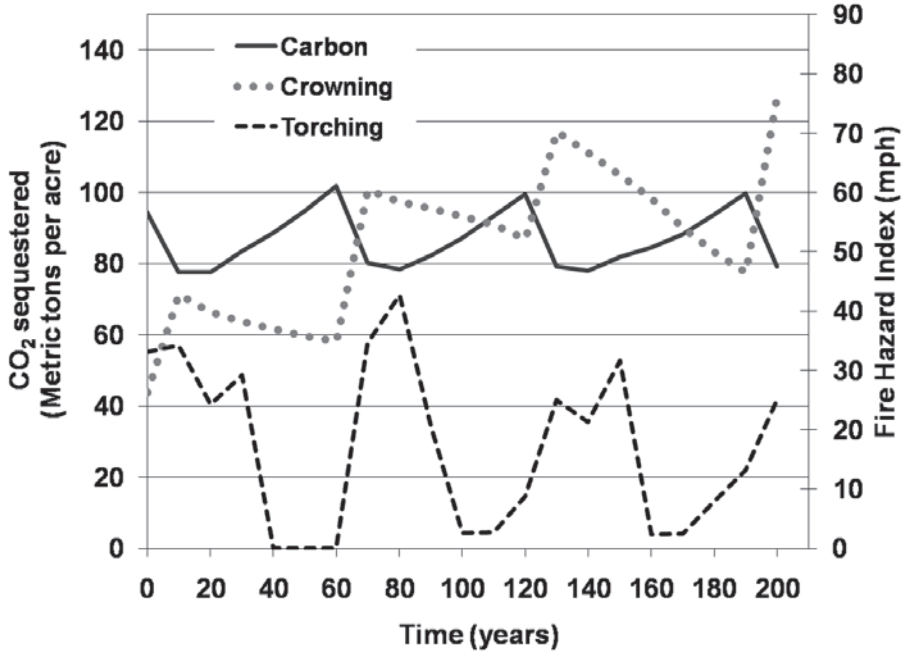

Figure 2—CO_2 equivalent per acre accumulated, potential CO_2 offsets, and the associated fire hazard for a stand maintained between 50 and 100 ft²/ac. The pre-treatment stand basal area was 100 ft²/ac and site index=45.

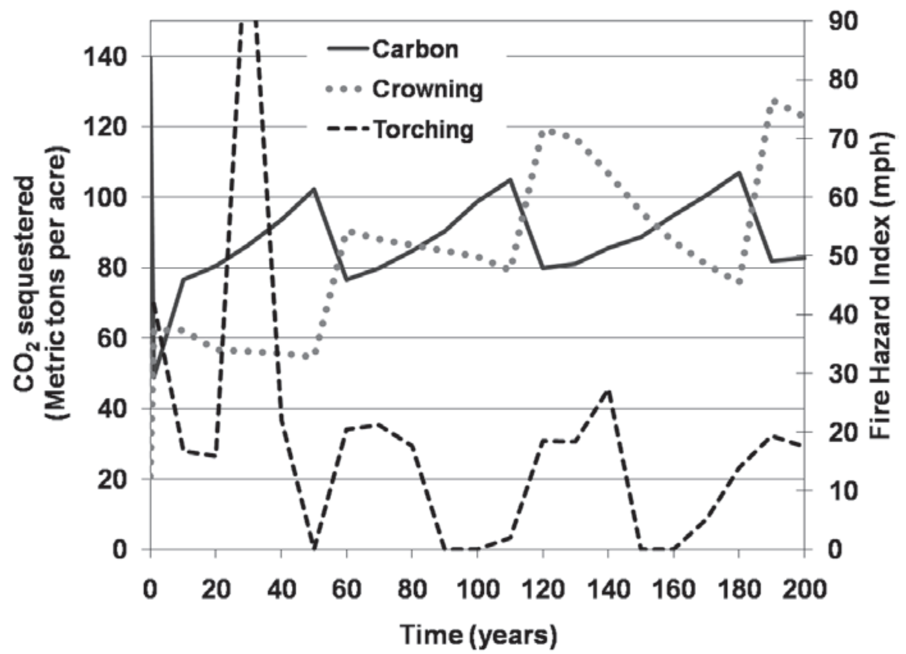

Figure 3—CO_2 equivalent per acre accumulated, potential CO_2 offsets, and the associated fire hazard for a stand maintained between 50 and 100 ft²/ac. The pre-treatment stand basal area was 160 ft²/ac and site index=45.

mulated more carbon, the crowning index decreased slightly, but never decreased to the pre-treatment value (figs. 2 and 3). This pattern continued throughout the simulation.

Although active crown fire risk was decreased, the success of thinning from below to prevent passive crown fire (crown fire initiation) was variable for both maintenance scenarios (figs. 2 and 3). For both scenarios, the torching index would increase substantially after each entry for about 30 years, but it would decrease due to the ingrowth of new tree regeneration.

The carbon consequences of maintaining stands at tree densities that reduce crown fire risk differed depending on the initial pre-treatment basal area. In the scenario where initial basal area was 100 ft^2/ac, thinning from below to 50 ft^2/ac would provide approximately 18 CO_2 MT/ac in the initial harvest (fig. 2). However, the scenario where initial basal area was 160 ft^2/ac and was thinned from below to 50 ft^2/ac would provide approximately 38 CO_2 MT/ac in the initial harvest (fig. 3). Throughout the next several rotations, thinning from below occurred whenever the basal area reached 100 ft^2/ac. For the scenario that was initially at 100 ft^2/ac, each maintenance harvest yielded approximately the same amount of CO_2 MT/ac as the initial harvest (fig. 2), replacing the carbon harvested each rotation. However, the scenario that was initially at 160 ft^2/ac only yielded approximately 20 CO_2 MT/ac in the maintenance harvests, never fully replacing the carbon harvested in the initial harvest (fig. 3).

Reforestation of Hayman Fire

The CO_2 equivalent accumulation rates for tree planting within the Hayman wildfire burn area varied with site index and planting density, but planting density was more important in determining carbon accumulation (table 2). After 90 years, forest CO_2 equivalent ranged from 22.5 to 50.1 MT CO_2/ac for a planting density of 100 trees per acre, 34.2 to 80.2 MT CO_2/ac for a planting density of 200 trees per acre, and 42.8 to 102.3 MT CO_2/ac for 300 trees per acre.

Reforestation: Future CO_2 Offsets and Fire Risk

The potential carbon offsets and associated fire risk for reforested stands differed depending on the management regime. The amount of CO_2 that accumulated after 400 years and available for an offset at the end of a 400-year rotation was 143 CO_2 MT/ac (fig. 4). For the stands that were maintained to reduce fire hazard, the CO_2 offsets from the harvests combined with the end of the 400-year rotation would yield 108 CO_2 MT/ac (fig. 5). The consequence of increased carbon sequestered in the *no thin* scenario was a higher risk for active crown fire with crowning indices ranging between 20 and 40 mph for the majority of the rotation (fig. 4).

Table 2—Metric tons of CO_2 equivalent per acre accumulated 90 years after a reforestation effort for different site productivities and ponderosa pine planting densities within the Hayman Fire on the Pike and San Isabel National Forest, Colorado.

	Planting densities (Trees per acre)		
Site Index	**100**	**200**	**300**
	Metric tons of CO_2 equivalent per acre		
35	27.5	41.3	51.9
40	29.7	46.1	57.3
45	34.8	54.0	67.4
50	39.6	63.6	79.8
55	50.1	80.2	102.3

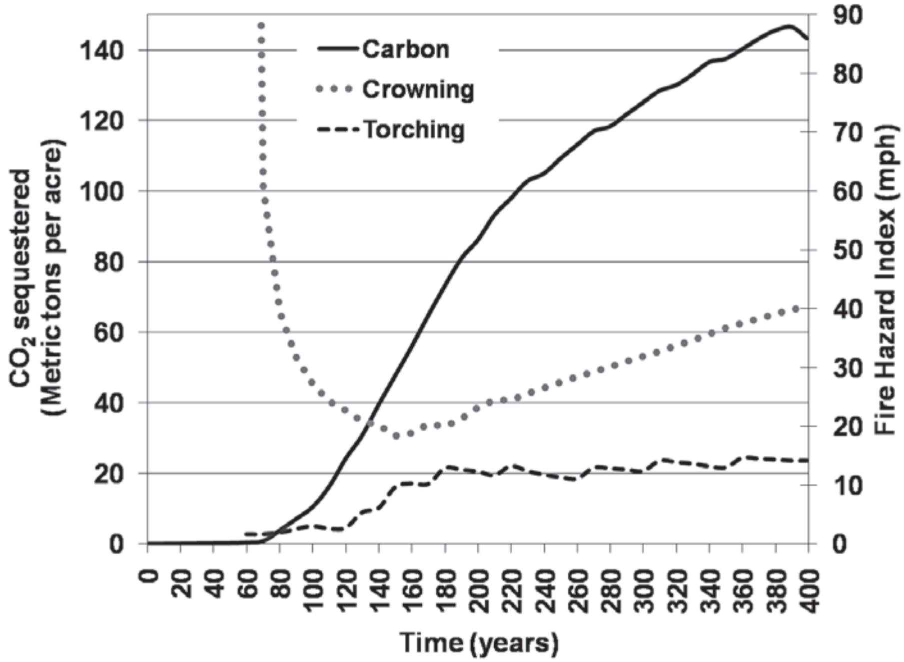

Figure 4—CO_2 equivalent per acre accumulated, potential CO_2 offsets, and the associated fire hazard for a reforested stand (site index=45) planted at a density of 450 trees per acre.

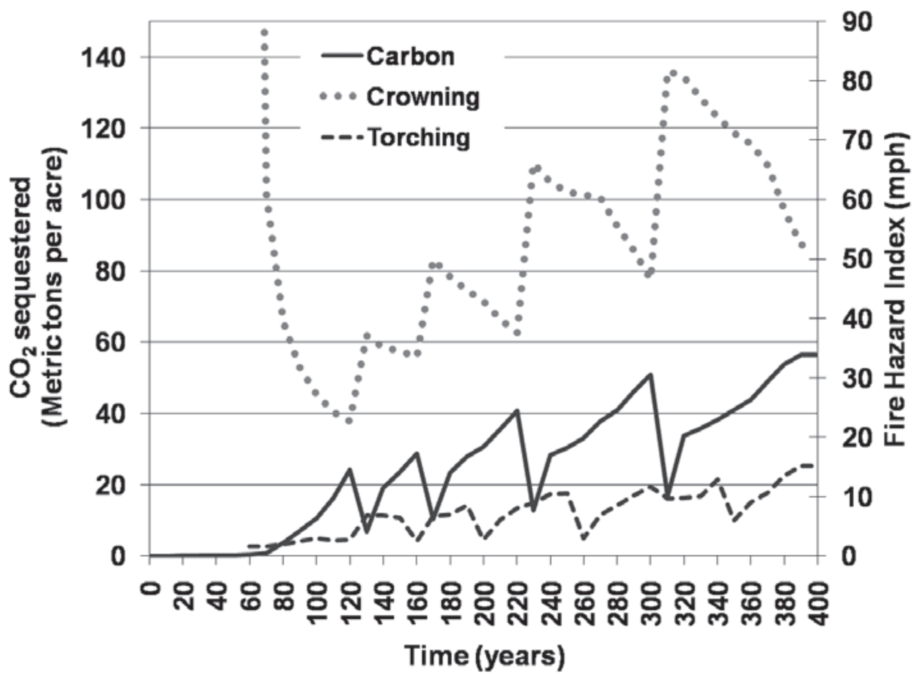

Figure 5—CO_2 equivalent per acre accumulated, potential CO_2 offsets, and the associated fire hazard for a reforested stand (site index=45) planted at a density of 450 trees per acre and maintained between 50 and 100 ft^2/ac.

In contrast, maintaining basal areas between 50 and 100 ft^2/ac resulted in lower active crown fire risk with crowning indices ranging between 40 and 80 mph (fig. 5). However, the risk of passive crown fire was high for both scenarios, with torching indices never exceeding 20 mph (figs. 4 and 5).

Discussion

The dense ponderosa pine/Douglas-fir forests of the Colorado Front Range currently serve as a carbon sink, but are at high risk for crown fire. Residents that live within the wildland urban interface and their urban counterparts recognize the increased wildfire risk (Kaval 2009) and are willing to pay to reduce the risk (Kaval 2009; Walker and others 2007). These residents favor thinning over prescribed fire (Walker and others 2007) to reduce crown fire hazard which will produce large quantities of non-merchantable material. If the biomass removed is not used as a substitute for fossil fuels then the area will become a carbon source. Also, maintenance of forests with low crown fire risk will result in lower carbon storage on the landscape.

Fuel treatments can reduce CO_2 emissions during a wildfire (Hurteau and others 2008) by reducing tree mortality and maintaining an intact post-fire forested stand. In our simulations, maintaining stand basal area between 50 and 100 ft^2/ac reduced the risk of a severe wildfire by substantially increasing the windspeed estimated to initiate a passive crown fire (torching event) or sustain an active crown fire. Other studies found similar results. In simulations of East Cascade ponderosa pine forests, the removal of understory vegetation led to a reduction in potential fire severity that consequently lowered overall biomass combustion (Mitchell and others 2009). A thin from below and whole-tree harvests were implemented, which resulted in several stand characteristics that reduce undesirable fire behavior (Agee and Skinner 2005). Thinning from below focuses on reducing the ladder fuel component of the stand, which raises the canopy base height of the stand. Taller canopy base heights place the flammable foliage further from the surface fuels and require taller and more intense flames for crown fire ignition. However, thinning from below may not accomplish target basal area reductions and some overstory may also need to be removed (Agee and Skinner 2005). In stands without a ladder fuel component, thinning would be focused in the overstory to reduce canopy bulk density in order to reduce crown fire risk.

As expected, in our simulations, as the residual trees grew and new regeneration established, stands added more foliage biomass, canopy bulk density increased, and canopy base height decreased. These changes in stand characteristics increased the fire risk until the next entry. Two things are notable. First, although the crowning index decreased throughout the rotation, it never reached the pretreatment values due to the lack of vegetation in the midstory, and met the objective of reducing active crown fire risk. Second, the torching index was variable throughout each rotation due to the ingrowth of regeneration that evidently reduced the average stand crown base height. It should be noted, however, that FVS is not a spatially explicit model and the placement of the regeneration in the understory is continuous. In reality, the regeneration could be quite patchy, creating situations in the stand where torching is more probable in one area versus another. Nevertheless, the lowering in torching index suggests that managers will need to have additional, more frequent entries that address the regeneration issue to maintain low crown fire hazard (Battaglia and others 2008).

While fuel treatments reduce the risk of severe wildfire and increase stand resiliency to fire, the removal of biomass from the stand also reduces the amount of carbon sequestered and produces carbon emissions (Finkral and Evans 2008;

Mitchell and others 2009; North and others in press). From a carbon standpoint, the thinning of forests to reduce fire hazard is only effective if a wildfire were to burn over the treated area within the rotation period. Therefore, if a wildfire doesn't burn over the fuel treatment, then that area will become a carbon source if the biomass removed is not used to replace fossil fuels to generate energy. The magnitude of the CO_2 emitted will depend on the equipment used for harvesting, the amount of biomass removed, the utilization of the material removed, and the biomass replaced during the rotation.

The potential amounts of CO_2 equivalent per acre emitted by fuel reduction treatments in the ponderosa pine/Douglas-fir forests of the PSINF will vary depending upon site productivity and thinning intensity if the biomass is not utilized to offset fossil fuels (table 1). In our simulations, stands with a high basal area (160 ft^2/ac) did not replace the carbon removed in the first thinning, because they were maintained at a lower basal area. Stands with lower basal area (100 ft^2/ac) would regrow the biomass removed, because the target for the next entry was 100 ft^2/ac. In the 160 ft^2/ac basal area stand, even if all the removed biomass was used as a substitute for fossil fuels, this treatment would still emit about 18 MT CO_2/ac, because the stand did not fully replace the carbon removed in the first entry. However, if a wildfire burned either of these treated areas, the stands would likely remain intact and CO_2 emissions would be lower than if not treated.

Assessing the carbon value of fuel reductions weighed against potential losses in a stand-replacing fire is complicated, but requires consideration of the total area treated and the probability of fire in that area if not treated. For any individual stand that burns, the calculation is fairly simple, and depends on the probability of regeneration. If a wildfire does burn over an untreated area the amount of CO_2 emitted over time would be substantial (Hurteau and others 2008), with initial losses from combustion of the foliage, small twigs, forest floor, and some dead wood, and subsequent losses from decomposition of the killed trees. If the burned area was small enough to be near live trees with seeds, natural regeneration would establish a new forest, and the area would eventually recover most or all of the carbon lost. Contemporary wildfires in ponderosa pine forests often produce large patches far from seed sources that prevent natural regeneration (Bonnet and others 2005; Lentile and others 2005; Romme and others 2003). In this case, unless replanted, the forest will change to a meadow and lose substantial carbon. But, fires do not always conveniently burn only the treated areas, and thinned areas are a substantial carbon source unless the biomass removed is used instead of fossil fuel and the trees allowed to regrow the carbon lost. If the entire PSFNF ponderosa pine/Douglas-fir zone were treated for fuels reduction, we estimate that about 60 percent of the biomass carbon would be moved from the forest to the atmosphere *unless* it was used for biomass fuel and the forest allowed to regrow. Contrast this with a historic probability of wildfire of ~2 percent of forested area per year, with a lower amount of area in a large, high severity burn that would preclude timely natural regeneration. From a carbon perspective, large-scale fuel treatments are likely to be a carbon source, *unless* biomass is used for fuel.

In our reforestation simulations, more carbon accumulated within 90 years as site productivity and planting densities increased (table 2). At sites with low productivity (SI=35), planting densities of 300 TPA would yield similar CO_2 equivalent sequestration as planting densities of 100 TPA on a higher site productivity of 55. These differences in CO_2 equivalent accumulated based on planting densities and site productivity should help guide managers with strategic reforestation planning. However, high planting densities would recreate forests with high active crown fire and bark beetle risk and more need for thinning, while low planting densities would not. Instead, low planting densities would develop forests with lower crown base heights more susceptible to passive crown fire. In our reforestation simulation, the *no thin* scenario sequestered more CO_2 than the *fuel treatment* scenario. After a 120 years of stand development, the active crown fire hazard was high (30 mph) and the stands were in potential danger of high mortality and substantial CO_2 release. The *fuel treatment* scenario follows the same story as mentioned in the fuel treatment maintenance scenario above; increase in CO_2 sequestered and lower fire risk over several rotations. The *no thin* scenario continues to accumulate CO_2 throughout the simulation, but density-dependent mortality begins around 180 years. Also around this time, basal areas are exceeding 180 ft^2/ac, making this stand highly susceptible to mountain pine beetle (*Dendroctonus ponderosae*) attack (Schmid and others 1994). Crown fire risk is moderate, with windspeeds less than 40 mph required to sustain an active crown fire due to the dense overstory canopy. The risk of passive crown fire is high in both scenarios, suggesting that some additional treatments such as pruning in the *no thin* and addressing the regeneration issue in the *fuel treatment* scenario is needed.

Conclusions

Many acres in the ponderosa pine/Douglas-fir forests of the Colorado Front Range are currently sequestering substantial amounts of carbon, but are also at high risk of sustaining a crown fire if ignited. Thinning these stands to reduce crown fire risk will result in CO_2 emissions if the biomass is not used as a substitute for fossil fuels. Furthermore, if stands are maintained at densities that are lower than the pre-treatment basal area, carbon will move from the forest to the atmosphere because the carbon from the total biomass removed will not be recovered. From a carbon standpoint, the argument that thinning a forest to reduce crown fire risk and CO_2 emissions is valid, but only if a fire actually burns the dense stand. Regardless of the carbon impact, thinning ponderosa pine/Douglas-fir forests to reduce crown fire risk has other ecological benefits.

A recent report by the Front Range Fuel Treatment Partnership concluded that heating with woody biomass in institutional buildings along the Colorado Front Range appears to be the best opportunity to lower fuel reduction treatment costs while utilizing woody biomass (FRFTP 2006). The FRFTP estimates that institutional buildings require only ~300 tons of woody biomass a year, which is feasible in terms of the level of forest treatment and transportation activity that is sustainable and desirable. Furthermore, the demand for institutions heated by biomass along the Colorado Front Range is expected to rise due to the building of new schools and existing schools that will replace aging boilers in the next few decades. Since most of the public institutions along the Colorado Front Range are dispersed within the same forests that need treatment, transportation costs to individual boilers would likely be cheaper than transporting it to a centralized biopower facility. However, until the infrastructure is developed, the utilization of biomass generated from fuel reduction treatments will remain a challenge.

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