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The effects of bark beetle outbreaks on forest development, fuel loads and potential fire behavior in salvage logged and untreated lodgepole pine forests

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ABSTRACT

Recent mountain pine beetle infestations have resulted in widespread tree mortality and the accumulation of dead woody fuels across the Rocky Mountain region, creating concerns over future forest stand conditions and fire behavior. We quantified how salvage logging influenced tree regeneration and fuel loads relative to nearby, uncut stands for 24 lodgepole pine forests in north-central Colorado that had experienced >70% overstory mortality from mountain pine beetles. We used our field measurements to predict changes in fuel loads and potential fire behavior in the forests that develop over the century following the outbreak and associated harvesting. Our field measurements and stand development projections suggest that salvage logging will alter the potential for canopy fire behavior in future stands by creating conditions that promote regeneration of lodgepole pine and quaking aspen as opposed to subalpine fir. The abundant subalpine fir that has regenerated in untreated, beetle-killed stands is predicted to form a stratum of ladder fuels more likely to allow fires burning on the surface to spread into the forest canopy. Harvesting increased woody surface fuels more than 3-fold compared to untreated stands immediately after treatments; however, coarse fuels will increase substantially (by ~55 Mg ha^{-1}) in untreated stands within three decades of the beetle infestation as dead trees topple, and the elevated fuel loads will persist for more than a century. Though salvage logging will treat a small fraction of beetle-infested Colorado forests, in those areas treatment will affect stand development and fuel loads and will alter potential fire behavior for more than a century.

1. Introduction

The majority of the mature lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex Wats.) forests in the central and southern Rocky Mountains originated after stand-replacing wildfires or logging (Brown, 1975; Lotan and Perry, 1983; Romme, 1982; Sibold et al., 2007). Since 1996, mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreaks have created a dramatic and widespread disturbance (>1.4 million hectares) of pine forests in Colorado and southeastern Wyoming (USDA, 2010a) that will shape forest dynamics for the coming century. For a subset of these forests (<20%), post-beetle logging will further modify ecosystem development (Collins et al., 2010, 2011). Compared to the ample documentation of how lodgepole forests recover after fire and harvesting (Lotan and Perry, 1983), the trajectory of stand development and forest disturbance set in motion by bark beetle outbreaks is poorly understood.

The growth responses of newly-recruited tree seedlings and surviving understory trees will determine the species composition, rate of stand development and fire behavior following bark beetle infestation. For example, residual conifers grew 3-fold faster for several decades after beetle-caused pine mortality in northwest Wyoming forests (Romme et al., 1986). High densities of new seedlings and the increased growth of remaining live trees in heavily-infested forests (70–90% of pine basal area) at the Fraser Experimental Forest in north-central Colorado are projected to return stand basal area and canopy fuels to pre-infestation levels within 80–100 years (Collins et al., 2011). Elsewhere in Colorado, lodgepole pine-dominated stands that lost <50% of their overstory to bark beetles in the 1980s returned to pre-infestation stand structure within three decades (Pelz, 2011). Observed and projected increases in subalpine fir after beetle infestation (Collins et al., 2010, 2011; Diskin et al., 2011; Page and Jenkins, 2007a) will create intermediate-height fuels that allow surface fires to burn into the forest canopy.

Concerns about wildfire and threats to infrastructure and human safety from falling beetle-killed trees have prompted harvesting of some infested stands (Fettig et al., 2007). Logging within these forests reduces canopy fuels, disrupting their horizontal and vertical continuity in an attempt to minimize crown fire hazard (Agee and Skinner, 2005; USDA, 2005). By removing large woody fuels (tree boles), salvage operations reduce fire line intensity, aid wildfire suppression and minimize soil heating effects caused

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by prolonged smoldering (Monsanto and Agee, 2008; USDA, 2005). Removal of standing, dead pine will restrict potential wildfire activity to surface fuels in the years immediately following treatment, yet as new stands develop the implications of harvesting for fire behavior and fire effects will be less certain. In spite of general public support for post-beetle outbreak forest operations (Western Governors' Association, 2002), salvage logging remains highly controversial (Donato et al., 2006; Newton et al., 2006), so managers must base their actions on well-designed research that evaluates multiple alternatives.

Post-beetle salvage logging has the potential to influence tree seedling recruitment, fuel loads and fire behavior for many decades following the current outbreak. Our research objectives were to characterize the post-outbreak forests, fuels and fire potential in harvested and untreated stands and to project how conditions will change as forests recover from the current bark beetle outbreak in north-central Colorado. Sampling was conducted $\sim$5 years after the onset of the current infestation, once needles had dropped ("gray phase") and harvesting had ended. Forest and fuels measurements from gray phase stands and nearby harvest areas were used to project stand structure, fuel loads, and potential fire behavior during the century following the outbreak and associated salvage treatments.

2. Methods

2.1. Study area and site selection

This study was conducted in 24 pairs of harvested and untreated sites in northern Colorado. Sites were distributed among four mountain pine beetle management areas on the Medicine Bow–Routt (Yampa and Parks Ranger Districts) and the Arapaho-Roosevelt (Fraser Experimental Forest/Sulfur Ranger District) National Forests and on the Colorado State Forest (Table 1). Each management area contained six sets of harvested and adjacent uncut, beetle-killed stands. Widespread lodgepole pine mortality from mountain pine beetle began in these areas between 1998 and 2002 (USDA, 2010a). Salvage logging to remove dead overstory pine and retain live overstory and understory (<15 cm diameter) conifers was conducted in 2008 and 2009 (USDA, 2005).

Study areas were selected to minimize differences in forest species composition and site conditions between adjacent harvested and untreated stands. We used pre-harvest stand exams of harvested areas (USFS Region 2 and Colorado State Forest Service, unpublished records) and our inventories of the uncut areas (described below) to confirm these similarities. Lodgepole pine was the dominant overstory species in both the harvest areas and nearby uncut stands and averaged between 70% and 90% of the overstory cover and basal area in association with a mixture of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and quaking aspen (*Populus tremuloides* Michx.). Harvested areas ranged from 5 to 30 hectares and were located less than 400 m from paired untreated stands. Abiotic site conditions (elevation, aspect and slope) were similar between treatments, differing by less than 100 m, 25° and 8%, respectively. At the Fraser Experimental Forest, treated and untreated areas were partitioned from uniform stands prior to timber sale layout and harvesting. In the three other management areas, uncut sites were reserved from suitable harvest areas for reasons not associated with stand structure or site differences, such as the presence of wildlife nests or logging layout.

2.2. Post-outbreak and post-treatment stand structure and surface fuels

The diameter, species and condition (live or dead) of trees $\geqslant$2.5 cm diameter at 1.4 m (diameter at breast height; DBH) were recorded in three 100 m by 5 m belt transects randomly located in each harvested and uncut area. Advance regeneration (trees <2.5 cm DBH and >2 years old) and recruitment (seedlings $\leqslant$2 years old) were enumerated in two 3.6 m radius circular plots at the ends of each transect.

Surface fuel loads were measured using the planar intersect method (Brown, 1971) on two 15 m transects per overstory transect (6 fuel transects per harvest unit or uncut stand). The diameters of individual pieces of surface wood were measured and partitioned into size classes based on the theoretical time required to respond to changes in atmospheric moisture (1, 10, 100, 1000 h fuels) (Fosberg, 1970). The 1 (0–0.64 cm) and 10 h (0.64–2.54 cm) fuel size classes were measured along the first 2 m, and the 100 (2.54–7.62 cm) and 1000 h (>7.62 cm) fuels were measured along the first 3 m and entire 15 m of each transect, respectively (Brown et al., 1982). Large wood ($\geqslant$7.62 cm in diameter) was classified as rotten or sound. Litter and duff depths were measured at three evenly spaced points along each transect.

2.3. Forest stand and fuel dynamics

We used our overstory structure, advance regeneration, seedling recruitment and surface fuel inventories to project changes in stand structure and fuel loads for harvested and uncut stands over 110 years. We used the Central Rockies Variant of the Forest Vegetation Simulator (FVS), a set of allometric equations used to model tree growth in Colorado, New Mexico, Arizona and South Dakota forests, to predict stand development (Dixon, 2002 and 2008). FVS estimates tree growth, mortality and recruitment based on site inventories of species, stand density, basal area, site index and overstory crown cover and has been validated by decades of natural resource studies. To refine estimates of recruitment over the course of stand development we used US Forest Service Forest Inventory and Analysis data from Colorado lodgepole pine stands using the Regeneration Imputation Extractor (REPUTE) (USDA, 2010b; Vandendriesche, 2010).

2.4. Fire behavior

We simulated fire behavior at various stages of stand recovery after the beetle outbreak and associated management using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston, 2003; USDA, 2011). The model combines information on species composition, stand structure

Table 1
Site description and average (range) climate conditions for mountain pine beetle management areas in north-central Colorado (RAWS, WRCC, 2011). Each management area consisted of six untreated and six harvested stands.

Project area	Elevation (m)	Mean annual temperature (°C)	Mean annual rainfall (cm)	Site index (m)
Fraser	2753 (2661–2860)	1 (−40–32)	37	19.8
Gore Pass	2853 (2780–2979)	2 (−39–31)	31	18.3
State Forest	2799 (2670–2980)	2 (−38–31)	35	19.8
Willow Creek	2827 (2751–2955)	3 (−36–32)	41	16.5

Table 2
Local conditions of hot and dry weather during peak fire season (July 1st–September 30th) at the Harbison Meadow, Dowd Junction, Willow Creek and Porcupine Creek, Colorado remote automatic weather stations (RAWS, WRCC, 2011) from 1986 to 2010. Wind speed indicates 1 min gusts measured 6.1 m above the ground surface. 1, 10, 100 and 1000 h fuels correspond to woody material 0–0.6, 0.6–2.5, 2.5–7.6, and >7.6 cm in diameter, respectively.

Percentile weather	Maximum temperature (°C)	Wind speed (km h^{-1})	Fuel moisture					
			1 h (%)	10 h (%)	100 h (%)	1000 h (%)	Herbaceous plants (%)	Woody plants (%)
97th	28.6	27.3	2.5	3.8	7.5	10.6	39.1	76.5
90th	26.6	22.5	3.3	4.8	9.0	12.1	48.9	86.3
80th	25.2	19.3	4.0	5.6	10.3	13.3	54.8	95.7
50th	22.2	16.1	6.1	8.5	13.3	15.5	72.7	115.0

Table 3
Overstory composition and structure (trees >10 cm at 1.4 m) in untreated ($n = 24$) and harvested ($n = 24$) stands. Data are means and (SE) for 24 untreated and 24 harvested stands. Dead trees include mortality caused by any means.

	Stem density		Basal area	
	Live (trees ha^{-1})	Dead (trees ha^{-1})	Live (m^2 ha^{-1})	Dead (m^2 ha^{-1})
Untreated				
Lodgepole pine	220 (30)	567 (35)	4.4 (0.5)	26.3 (1.8)
Subalpine fir	22 (6)	1 (1)	0.6 (0.2)	0.1 (0.1)
Engelmann spruce	14 (6)	1 (1)	0.4 (0.2)	0.1 (0.1)
Quaking aspen	56 (17)	41 (10)	1.6 (0.7)	0.7 (0.2)
Harvested				
Lodgepole pine	77 (18)[**]	75 (15)[**]	1.2 (0.3)[**]	2.4 (0.5)[**]
Subalpine fir	3 (2)	0 (–)	0.1 (0.0)	0.0 (–)
Engelmann spruce	1 (1)[**]	0 (–)	0.0 (-)[*]	0.0 (-)
Quaking aspen	24 (10)	12 (5)[**]	0.5 (0.2)	0.2 (0.1)[**]

[*] Significant difference from untreated stands at the $\alpha = 0.10$ level.
[**] Significant difference from untreated stands at the $\alpha = 0.05$ level.

(canopy bulk density and base height), and surface fuel loads to estimate fire behavior and fire effects (loss of live basal area) for a range of weather conditions. For each combination of stand and weather conditions, the model estimates the minimum wind speed needed to move wildfire from the surface into tree canopies (torching index) and to spread fire between tree canopies (crowning index). For both indices, lower wind speed thresholds indicate that crown fire activity is more likely (Scott and Reinhardt 2001).

For the initial stage of stand development FFE-FVS selected a combination of fuel models to best characterize the measured fuel loads, described above. For each subsequent time period, FFE-FVS created an optimal combination of fuel models to describe the projected stand and fuel conditions generated by FVS, also described earlier. By creating a weighted average from multiple fuel types this approach better describes complex fuel profiles and generates more realistic flame length estimates (Johnson et al., 2011). In addition to the changes in canopy bulk density with shifts in species composition and stand structure, FFE-FVS accounts for changes in litter and snag inputs, understory growth and decomposition to estimate future surface fuel loads.

Local weather conditions were summarized for the peak fire season (July 1–September 30) from air temperature, fuel moisture and wind speed records for four Remote Automatic Weather Stations (Dowd Junction, Harbison Meadow, Porcupine Creek and Willow Creek) located within 40 km of the study areas (WRCC, 2011). A gradient of fire weather conditions (50th, 80th, 90th and 97th percentiles) for those variables was calculated from 1986 to 2010 (time period based on available data) (Table 2) using the FireFamily Plus statistical software package (Bradshaw and Brittain, 1999). Ten-minute average wind speed measurements were converted to 1 minute gusts (Crosby and Chandler, 2004).

2.5. Statistical analysis

We compared our field measurements of post-outbreak and post-treatment conditions (gray phase) and projected stand structure, fuel loads and fire behavior for 110 years in 24 pairs of untreated and harvested beetle-killed stands. The 24 harvested and 24 untreated stands were nested within four separate management areas located in north-central Colorado. Individual belt and planar transects and circular plots were composited within each of the harvested and untreated stands. We used a generalized linear mixed model (Proc GLIMMIX; SAS, 2009) with treatment (harvested vs. untreated) as fixed and management area as random effects to compare initial tree regeneration and surface fuel data. Our initial field measurements of species composition and density of tree regeneration (advance regeneration and new recruits) and fine surface fuel loads did not differ significantly among the four management areas, nor were there significant area *x* treatment interactions. As such, at ten year intervals for the first 110 years of forest recovery, the treatment effects on forest structure (tree density and basal area), fire behavior (crowning and torching indices), and fire effects (post-fire basal area) were tested with a t-test ($n = 24$). We verified normality and homogeneity of variance (Levene's test; Keyes and Levy, 1997) and assigned statistical significance at the $\alpha = 0.05$ level unless otherwise noted.

3. Results

3.1. Post-outbreak and post-treatment stand structure and surface fuels

Lodgepole pine accounted for 90% of the total overstory ($\geqslant 10$ cm DBH) basal area (live and dead) in untreated stands (Table 3). Pine beetles killed between 79% and 91% of overstory lodgepole pine basal area, equivalent to a 77% loss of the total live stand basal area on average. There were 312 live overstory trees ha^{-1} after the outbreak on average (range = 179–537 trees ha^{-1}) (Table 3). In untreated stands, densities of live understory (trees $\geqslant 2.5$ cm and <10 cm DBH), advance regeneration (trees >2 years old, <2.5 cm DBH) and seedling recruits (trees $\leqslant 2$ years old)

Table 4
Density (trees ha^{-1}) of understory (trees <10 cm, >2.5 cm DBH), advance regeneration (<2.5 cm DBH, >2 years old) and recruitment ($\leqslant$2 years old) in untreated ($n = 24$) and harvested ($n = 24$) stands. Data are means and (SE) for 24 untreated and 24 harvested stands.

	Understory trees	Advance regeneration	Seedling recruitment
Untreated			
Lodgepole pine	361 (86)	562 (104)	305 (108)
Subalpine fir 46 (11)	46 (11)	956 (193)	1114 (316)
Engelmann spruce	37 (13)	75 (19)	79 (28)
Quaking aspen 14 (6)	14 (6)	1093 (202)	114 *** (40)
Harvested			
Lodgepole pine	102 (22)**	669 (120)	3135 (714)**
Subalpine fir	20 (8)*	272 (103)**	144 (40)**
Engelmann spruce	12 (7)**	21 (9)**	4 (3)**
Quaking aspen	3 (1)*	1269 (252)	841*** (356)*

* Significant difference from untreated stands at the $\alpha = 0.10$ level.
** Significant difference from untreated stands at the $\alpha = 0.05$ level.
*** Aspen recruitment was the result of sprouting.

Table 5
Surface fuel loads (Mg ha^{-1}) in untreated and harvested stands. 1, 10, 100 and 1000 h fuels correspond to woody material 0–0.6, 0.6–2.5, 2.5–7.6, and $\geqslant$7.6 cm in diameter, respectively. Data are means and (SE) for 24 untreated and 24 harvested stands.

1 h	10 h	100 h	1000 h Sound	1000 h Rotten	Total woody	Litter	Duff
Untreated							
0.7	2.5	4.5	5.7	4.2	17.6	13.2	23.6
(0.0)	(0.3)	(0.8)	(1.1)	(0.7)	(1.8)	(0.7)	(1.6)
Harvested							
2.3*	10.0*	12.8*	19.8*	2.9	47.8*	14.3	22.6
(0.3)	(0.6)	(1.3)	(3.1)	(0.6)	(4.2)	(1.2)	(1.5)

* Significant difference from untreated stands at the $\alpha = 0.05$ level.

averaged 458, 2459 and 1612 stems ha^{-1}, respectively (Table 4). In contrast to the overstory, subalpine fir dominated the lower canopy strata of untreated stands, comprising 36% and 69% of the advance regeneration and seedling classes, respectively. Aspen density was 10-fold higher in the advance regeneration size class compared to the overstory, understory and seedling strata in untreated stands.

Overstory basal area was 87% lower in harvested vs. untreated stands with an average of 105 trees ha^{-1} (Table 3). The density of seedlings colonizing harvest units was significantly higher than in untreated stands (4124 vs. 1612 stems ha^{-1}); lodgepole pine seedlings represented three-quarters of all new seedlings in cut areas and were 10-fold more abundant than in untreated stands (Table 4). Aspen sprouts were 7-fold more abundant in harvest units compared to untreated stands.

The total mass of woody surface fuels averaged 17.6 Mg ha^{-1} in untreated stands and 47.8 Mg ha^{-1} in harvested units (Table 5). Harvesting significantly increased the mass of fine (1, 10, 100 h size classes) and sound, coarse (1000 h size class) fuels 3.3 and 3.5-fold compared to untreated stands, respectively. Harvesting had no effect on the dry mass of rotten, coarse fuels, litter or duff. Fine fuel loads did not differ significantly within each treatment among the four management areas.

3.2. Stand development

Our modeling predicts that the abundant sprouting documented by our field sampling will generate an increase in aspen that will peak four decades after the beetle infestation in both untreated and harvested stands (Fig. 1); on average during this period, aspen density will be higher in harvested stands ($p = 0.06$). Harvesting will favor increased lodgepole pine density, to pre-outbreak levels, following the decline of aspen. Our projections also predict that untreated stands will have a significantly greater density and basal area of subalpine fir compared to harvested stands throughout the simulation period. Pre-outbreak stand conditions (~35.5 m^2 ha^{-1} of basal area; quadratic mean diameter of 13.5 cm) are expected to recover after 75 and 90 years in untreated and harvested stands, respectively. Owing to a greater density of subalpine fir, canopy bulk density is predicted to be significantly higher in untreated stands compared to harvested areas after six decades (Table 6).

3.3. Surface fuel dynamics

Standing snags are projected to deteriorate and fall in the first three decades following beetle attack, adding branches and boles as surface fuels. Coarse wood mass will increase significantly (5.5-fold) above pre-infestation levels as dead trees topple in untreated stands. The consequences of the outbreak on coarse woody fuels will remain evident in untreated stands compared to pre-outbreak conditions or harvested stands for more than a century (Fig. 2). Harvesting causes an initial increase in fine surface fuels that will decompose within two decades (Fig. 2). Aspen mortality and conifer crown closure occurring 40–60 years after the outbreak are also projected to elevate fine fuels temporarily in harvested and untreated stands (Figs. 1 and 2).

3.4. Potential fire behavior and effects

Differences in tree species composition and canopy and surface fuel loads between untreated, beetle-killed stands and harvested areas will result in distinct torching and crowning indices and potential fire behavior (Table 6). Initially, the lack of canopy fuels will generate similar fire behavior in harvested and uncut stands, but harvested areas are likely to experience greater flame lengths and fireline intensities within the first two decades as a result of increased fine surface fuel loads. However, as the forest overstory develops, abundant subalpine fir will increase the canopy bulk density (CBD) of untreated stands. These crown conditions

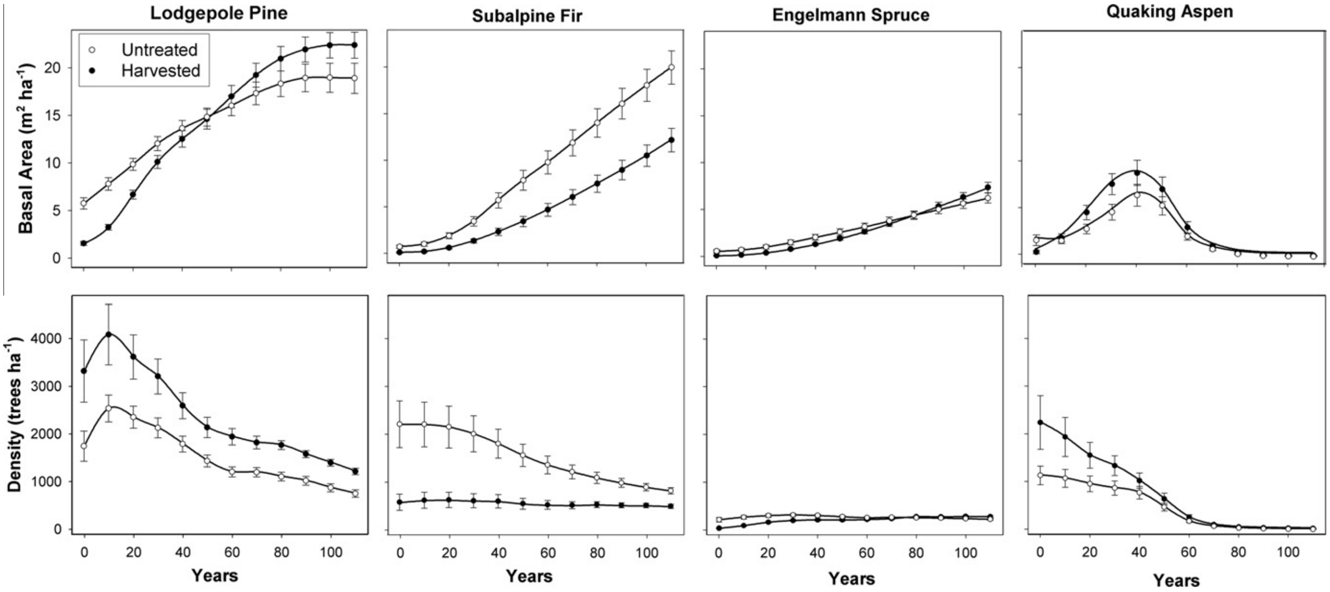

Fig. 1. Projected stand development based on initial observations in harvested (n = 24) and untreated stands (n = 24) in mountain pine beetle-infested lodgepole pine forests in Colorado. Growth was simulated using the Forest Vegetation Simulator (Dixon, 2002). Projections were based on observed regeneration, overstory conditions and site index (Tables 3 and 4). Whiskers indicate standard error.

Table 6
Torching and crowning indices (km h^{-1}) for a range of weather conditions in untreated and harvested beetle-infested forests. Indices are based on stand structure, canopy bulk density, fuel loads and moisture (Dixon, 2002; Reinhardt and Crookston, 2003). Torching and crowning indices are the wind speeds necessary to move fire from the ground surface into tree crowns and between canopies, respectively. Data are means and (SE) for 24 untreated and 24 harvested stands. Percentile of hot and dry weather is based on four remote automated weather stations (RAWS, WRCC, 2011) during peak fire season (July 1st–September 30th) from 1986 to 2010.

Years	Torching index				Crowning index				Canopy
	Percentile weather				Percentile weather				Bulk density
	50th	80th	90th	97th	50th	80th	90th	97th	(kg m^{-3})
Untreated									
0	121***	79	70	62	160***	135***	125***	114***	0.03
	(12.4)	(10.1)	(9.2)	(8.4)	(11.2)	(9.6)	(8.9)	(9.2)	(< 0.01)
20	6	4	3	3	72	60	56	51	0.10
	(3.3)	(2.6)	(2.3)	(1.9)	(4.0)	(3.4)	(3.2)	(2.9)	(0.01)
60	29	22	17	15	51	42	39	35	0.17
	(6.5)	(5.3)	(4.8)	(3.2)	(4.5)	(3.8)	(3.5)	(4.3)	(0.01)
110	48	36	29	25	34	28	26	23	0.21
	(5.5)	(4.3)	(3.9)	(3.4)	(1.5)	(1.3)	(1.2)	(1.2)	(0.01)
Harvested									
0	–****	–	–	–	–	–	–	–	<0.01**
									(<0.01)
20	7	2	2	1	77	65	60	54	0.09
	(1.4)	(0.8)	(0.6)	(0.5)	(4.0)	(3.6)	(3.1)	(2.0)	(<0.01)
60	72**	53**	46**	38**	60	51	47	42	0.14*
	(8.0)	(6.4)	(5.8)	(4.0)	(5.5)	(4.7)	(4.3)	(5.2)	(0.01)
110	81**	61**	53**	45**	38**	32**	30**	27**	0.17**
	(8.8)	(6.9)	(6.1)	(5.3)	(1.6)	(1.4)	(1.3)	(1.2)	(<0.01)

* Significant difference from untreated stands in the same weather conditions at the α = 0.10 level.
** Significant difference from untreated stands in the same weather conditions at the α = 0.05 level.
*** Wind speeds exceed all historical observations recorded for the study area.
**** Harvested areas did not have adequate fuel to sustain canopy fire immediately following treatment.

promote torching at significantly lower wind speeds and increase the likelihood of active crown fire as the stands mature (Table 6). As a result, passive crown fires (fires that ignite individual tree crowns, but do not spread between canopies) are expected to occur in untreated stands under average weather conditions (50th percentile weather); in contrast, under similar weather conditions surface fires are expected in harvested areas.

Regardless of treatment, the amount of basal area surviving a potential wildfire declines as weather conditions become more extreme (Table 7). However, the relative differences in survival following fires in harvested and untreated areas alternate as stands develop (Table 7). For example, post-fire tree survival is at least 10-fold greater in untreated compared to harvested stands the first decade after treatment. This pattern reverses once harvest residue decays and the understory canopy expands in untreated stands (after 60 years), such that the basal area surviving a potential wildfire is predicted to be somewhat greater in harvested areas in more extreme weather conditions.

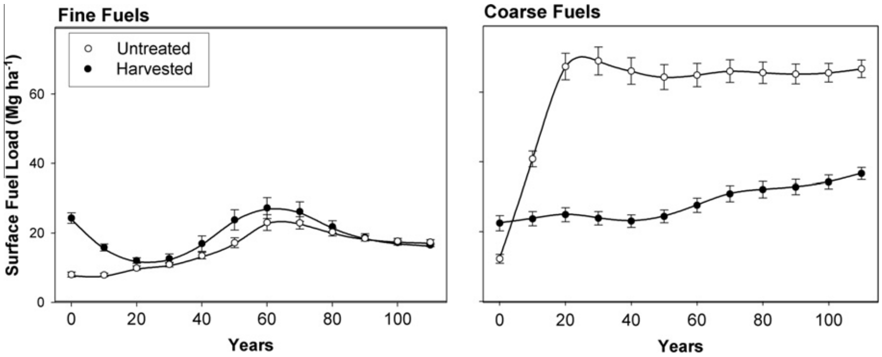

Fig. 2. Changes in surface fuel loads in harvested and untreated mountain pine beetle management areas as estimated by the Forest Vegetation Simulator (FVS) (Dixon, 2002; 2008). Projected changes based on initial observations of fuel loads in 24 untreated and 24 harvested areas (Table 5). Fine woody fuels are less than 7.6 cm in diameter (3 in.); coarse fuels (includes sound and rotten) are greater than or equal to 7.6 cm diameter. Whiskers indicate standard error.

Table 7
Residual basal area following potential wildfire in bark beetle-infested forests. Mortality, based on stand and fuel conditions, is estimated by FFE-FVS (Dixon, 2002; Reinhardt and Crookston, 2003) for a range of weather conditions. Data are means and (SE) for 24 untreated and 24 harvested stands. Percentile of hot and dry weather is based on four remote automated weather stations (RAWS, WRCC, 2011) during peak fire season (July 1st–September 30th) from 1986 to 2010.

Years	Pre-fire quadratic mean	Post-fire basal area			
		Percentile weather			
	Diameter (cm)	50th	80th	90th	97th
Untreated					
0	4.2 (0.3)	2.8 (0.38)	1.8 (0.21)	1.1 (0.40)	1.1 (0.17)
20	5.6 (0.2)	1.4 (0.21)	0.6 (0.15)	0.3 (0.14)	0.3 (0.01)
60	12.1 (0.3)	5.0 (0.54)	2.5 (0.43)	0.9 (0.30)	0.9 (0.08)
110	14.9 (0.4)	11.7 (0.91)	6.3 (0.94)	3.6 (0.81)	3.6 (0.41)
Harvested					
0	1.9 (0.2)	0.1 (0.09)**	0.1 (0.07)**	0.1 (0.03)**	0.1 (0.08)**
20	5.2 (0.2)	0.4 (0.14)**	0.4 (0.08)	0.2 (0.07)	0.2 (0.01)
60	12.4 (0.3)	5.8 (0.43)	3.3 (0.43)*	2.5 (0.43)**	2.5 (0.32)**
110	14.0 (0.4)	13.1 (0.86)	8.8 (0.99)*	5.5 (0.96)*	4.6 (0.61)*

* Significant difference from untreated stands in the same weather conditions at the $\alpha = 0.10$ level.
** Significant difference from untreated stands in the same weather conditions at the $\alpha = 0.05$ level.

4. Discussion

4.1. Fire behavior and effects as stands recover from bark beetle

Throughout the century following pine beetle infestation, fire behavior will be influenced by changes in canopy and surface fuel loads, species composition and stand structure. Within weeks of a successful beetle attack for example, foliar moisture declines and foliage flammability increases in infested pine trees (Jolly et al., 2012). As needles are shed from ‘red phase’ beetle-killed trees, the increase in fine and herbaceous fuels and projected changes in surface microclimate are likely to create conditions that cause greater flame lengths and heat release (Hicke et al., 2012; Jenkins et al., 2008; Page and Jenkins, 2007a, 2007b; Schoennagel et al., 2012); however other studies have found no significant change in surface fuels following mountain pine beetle outbreak (Hicke et al., 2012; Klutsch et al., 2009). Needles shed from dead pines will decrease understory shading, CBD, and the short-term crown fire hazard, compared to uninfested stands. Loss of overstory foliage stimulates growth of the understory trees (Collins et al., 2011) that will form an intermediate stratum of fuels and aid movement of wildfire into the forest canopy. Over the course of decades, windthrown beetle-killed trees will contribute large-size surface fuels (Mitchell and Preisler, 1998) and may increase the potential for severe and prolonged soil heating and production of airborne burning material (firebrands) and spot fires (Koo et al., 2010; Monsanto and Agee, 2008).

Fine fuel accumulation (Jenkins et al., 2008; Page and Jenkins, 2007b), growth of understory trees and plants (Collins et al., 2011) and changes in surface microclimate (surface wind speed and humidity) (Page and Jenkins, 2007a) associated with foliage and canopy loss cause conditions that promote the spread of surface fires after insect outbreaks (Hicke et al., 2012). The fine fuel loads we measured in beetle-killed stands in Colorado were within the range measured in other infested, lodgepole-dominated forests (4–14 Mg ha^{-1}; Klutsch et al., 2011; Page and Jenkins, 2007b; Simard et al., 2011); owing to the high variability in fine fuel loads in untreated forests, the increase attributable to beetle-caused tree mortality has been difficult to quantify. In contrast, we found that fine surface fuel loads were three times as high in salvage-logged areas compared to uncut stands. Such changes in surface fuel loads, coupled with the exposed microclimate found in recently-harvested areas, generate taller surface flame lengths and increased heat release (Rothermel, 1983). Nevertheless, decomposition of fine fuels and reduced litter inputs are projected to negate the post-outbreak and harvesting accumulation of fine fuels within two decades of treatment (Fig. 2).

The expected succession of tree species following bark beetle infestations of mature lodgepole forests will dictate changes in wildfire behavior for a century or more. Harvested stands will be colonized and populated by lodgepole pine seedlings that germinate from cones and seeds distributed on the forest floor in mineral soil exposed during harvesting (Lotan and Perry, 1983). Aspen sprouts will also be stimulated by overstory removal and soil exposure. Conversely, the density of shade-tolerant species (subalpine fir and Engelmann spruce) that were present in the understory of beetle-killed stands will decline in the higher light environment of the harvested areas (Table 4).

Wildfires that ignite in either untreated or harvested beetle-infested stands during the 10–15 years prior to recovery of a closed forest canopy will likely be restricted to surface combustion. Abundant aspen sprouting the first few decades after the outbreak will reduce the risk of extreme fire behavior owing to the high foliar moisture content of aspen and associated understory vegetation (Bigler et al., 2005; van Wagner, 1977). The progressive increase in subalpine fir that is projected over the course of stand development will increase the likelihood of crown fires in untreated forests. In contrast to lodgepole pine, subalpine fir retains lower branches and has a higher CBD (Brown, 1978; Despain and Sellers, 1977) that facilitates movement of wildfire from the surface into tree crowns (torching) and between canopies (crowning) (Baker, 2003; van Wagner, 1977). The increased abundance of subalpine fir in untreated, beetle-killed stands lowers the wind speed threshold needed to permit torching compared to harvested stands (Table 6). Similar to our study, the increased presence of subalpine fir measured in post-epidemic lodgepole pine stands in eastern Utah and in other Colorado sites created stands with lower canopy base height and greater potential for crown fire initiation (Klutsch et al., 2011; Page and Jenkins, 2007a, 2077b).

The canopy and surface fuels and predicted fire behavior in gray phase and salvage-harvested stands differ from pre-infestation forests. For mature lodgepole pine forests dominated by green trees, CBD averages $\sim$0.15 kg m^{-3} as opposed to <0.08 kg m^{-3} that we and others (Klutsch et al., 2011; Simard et al., 2011) have estimated for beetle-infested stands. From the time needles are shed and extending for several decades, the low CBD of beetle-killed trees reduces the likelihood of active crown fires compared to green, pre-infestation stands. The chance of active crown fire remains uniformly low in both untreated and harvested stands until CBD recovers to pre-infestation levels. Residual live trees in untreated stands will speed the return of pre-infestation CBD by several decades compared to the recovery of harvested areas.

Windthrow of beetle-killed snags will greatly increase coarse surface fuel loads and the severity of potential wildfires burning in untreated stands (Andrews et al., 2011; Brown, 1975; Kulakowski and Veblen, 2007). We estimate that wind-thrown snags occurring over several decades will cause a > 5-fold increase in the coarse surface fuels mass in untreated stands, compared to the gray phase measurements we report here (68 vs. 12 Mg ha^{-1}; Fig. 2). Elevated coarse fuel loads should persist beyond the simulation period owing to the long turnover time (>300 years) of lodgepole pine coarse fuels in cool, high altitude Colorado forests (Kueppers et al., 2004). For comparison, uninfested, central Rocky Mountain, subalpine forests contain 22–42 Mg ha^{-1} of coarse surface fuels (Graham et al., 1994). For Utah forests that lost 80% of their overstory lodgepole pine to bark beetles, two-thirds of dead trees toppled within 20 years of the infestation and resulted in 51 Mg ha^{-1} of coarse surface fuels (Page and Jenkins, 2007b). Similarly, coarse fuels measured 30 years after a bark beetle outbreak in central Colorado lodgepole-dominated stands totaled 53 Mg ha^{-1} (Pelz, 2011).

4.2. Fuel reduction treatment effectiveness

Our findings suggest that salvage logging of gray phase, beetle-killed, lodgepole pine stands will alter the behavior and severity of potential future wildfires. Harvesting decreased the density of subalpine fir and lowered CBD compared to uncut stands after six decades of stand recovery (Table 6). Conversely, harvesting promoted establishment of lodgepole pine and aspen sprouting (Fig. 1). The canopy profiles of both these species hinder torching and increase post-fire tree survival in mature stands under severe weather conditions (Tables 6 and 7). Harvesting reduced coarse fuel loads by >50% compared to untreated stands (Fig. 2). In the event of a post-infestation wildfire, the lower coarse fuel load would reduce the duration and magnitude of soil heating known to damage plant root systems and soil biota, to increase soil losses and to delay post-fire ecosystem recovery (Monsanto and Agee, 2008; Moody and Martin, 2001). Coarse surface fuels also threaten to increase the extent and duration of wildfire events through prolonged smoldering and by serving as sources and receptors of firebrands that promote spotting and crowning in adjacent stands (Hyde et al., 2011; Koo et al., 2010). Fuel reduction operations in subalpine forest typically aim to retain 22–44 Mg ha^{-1} of coarse surface fuels to limit severe fire effects and facilitate potential fire suppression activities (J. Underhill, Pike-San Isabel NF, pers. comm.; USFS, 2005). These wood retention guidelines are also used to ensure adequate habitat for small organisms and nutrient cycling associated with decaying large wood (Harmon et al., 1986; Spies et al., 1988). On average, the harvest units we studied were within this range (Table 5).

Although more than thirty studies have examined the potential impact of bark beetles on surface fuel loads and subsequent wildfire, there are still significant knowledge gaps in our understanding of bark beetle/fire interactions including snag and litter deposition rates, altered wind speeds, and changes in fuel moisture associated with changes in surface microclimate (Hicke et al., 2012). Furthermore, patchy tree mortality, variable foliar moisture, needle loss and changes in CBD over time are all likely to contribute to fire behavior that is poorly represented by current models. All models are constrained by their underlying assumptions and data input needs, but new models that better account for spatial and temporal sources of heterogeneity in fuel loads and canopy moisture levels should improve predictions regarding fire behavior in beetle-killed forests (Jolly et al., 2012).

In southern Rocky Mountain lodgepole forests, stand-replacing fires typically occur during periods of prolonged drought (Finney et al., 2003; Kulakowski and Jarvis, 2011; Turner and Romme, 1994). As weather conditions become more extreme (hotter, drier, windier), wildfire behavior is less reliant on the stand structure or fuel loads of these forests (Bigler et al., 2005; Finney et al., 2003). As such, under extreme weather conditions fire behavior might differ little between beetle-killed and green forests. Our projections suggest that harvesting will impact potential fire behavior, yet stand-scale salvage operations will treat a small fraction (<20%) of beetle-infested Colorado forests (Collins et al., 2010), so the implications of these treatments for landscape-scale wildfire may be modest (Kulakowski and Jarvis, 2011; Kulakowski and Veblen, 2007). Much remains to be learned about wildfires in recovering beetle-killed forests, though the differences in species composition and fuel loads we predict based on measurements in harvested stands and untreated beetle-killed forests provide land managers an initial estimate of how these alternatives influence potential fire behavior and severity over the coming century.

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