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Short-term impact of post-fire salvage logging on regeneration, hazardous fuel accumulation, and understorey development in ponderosa pine forests of the Black Hills, SD, USA

Tara L. Keyser[A,B,D], *Frederick W. Smith*[A] *and Wayne D. Shepperd*[C]

[A]Colorado State University, Department of Forest, Rangeland, and Watershed Stewardship, Fort Collins, CO 80523, USA.
[B]Present address: US Department of Agriculture, Forest Service, Southern Research Station, Bent Creek Experimental Forest, 1577 Brevard Road, Asheville, NC 28806, USA.
[C]US Department of Agriculture, Rocky Mountain Research Station, 240 W Prospect, Fort Collins, CO 80526, USA. [Retired]
[D]Corresponding author. Email: tkeyser@fs.fed.us

Abstract. We examined the impacts of post-fire salvage logging on regeneration, fuel accumulation, and understorey vegetation and assessed whether the effects of salvage logging differed between stands burned under moderate and high fire severity following the 2000 Jasper Fire in the Black Hills. In unsalvaged sites, fire-related tree mortality created a large standing pool of available fuel, resulting in a rapid increase in surface fuel loads. After 5 years, fine woody debris (FWD) and coarse woody debris (CWD) increased ~1380% and 980% in unsalvaged sites, resulting in FWD and CWD loads of 13 and 25 Mg ha^{-1}, respectively. In contrast, salvage logging limited the rate of accumulation of FWD to ~110% over the same time period and total accumulation of CWD to 16 Mg ha^{-1}. In moderate-severity sites, regeneration was 75% lower in salvaged sites owing to low seed-tree retention, suggesting a re-evaluation of salvage guidelines during future operations in the Black Hills. The likelihood of timely regeneration in high-severity sites, regardless of salvage treatment, is low. We found no discernible effect of salvage logging on understorey development 5 years after fire. Logging caused neither a reduction in total plant cover nor an increase in the abundance of exotic species.

Additional keywords: exotic species, fuel load, mixed-severity, *Pinus ponderosa*, wildfire.

Introduction

Immediately following large-scale wildfires, managers must make complex decisions regarding the necessity for post-fire rehabilitation measures including salvage logging. Salvage logging recovers value from fire-killed and fire-damaged trees (Sessions *et al*. 2004; Akay *et al*. 2006). In addition, concerns over fuel accumulation have been used by land-management agencies to justify post-fire salvage logging (USDA Forest Service 2000, 2004). Increased surface fuel loads are thought to increase fire hazard and the severity of subsequent wildfire (Brown *et al*. 2003). The efficacy of salvage harvesting in reducing post-fire fuel loads, future fire hazard, and potential fire severity, however, is controversial. A recent study following the Biscuit Fire in Oregon suggests that post-fire salvage logging increases rates of hazardous fuel accumulation and future fire risk as well as reduces establishment of natural regeneration (Donato *et al*. 2006). Similarly, an analysis examining the patterns of fire severity left by the Biscuit Fire has shown that salvage logging 15 years before the Biscuit Fire may have increased burn severity within the previously salvaged areas (Thompson *et al*. 2007); however, the contribution of prefire fuel loads to fire severity in the reburned salvaged areas was unknown. Other negative effects associated with salvage logging include delayed recovery of the understorey herbaceous and shrub layer (Stuart *et al*. 1993). The present study was designed to examine the ecological effects on sites that were salvaged after fire *v.* sites that were not salvaged after fire as a function of fire severity (moderate and high). Specifically, we ask how post-fire salvage logging influences the response of fine and coarse woody debris and the recruitment and recovery of vegetation (natural tree regeneration and establishment and herbaceous and shrub response) at 2 and 5 years after harvest.

The accumulation of surface fuels following wildfire is a concern of land managers often used to justify post-fire salvage logging. Surface fuel loads are greatly reduced by wildfire, but with time quickly increase, greatly exceeding prefire amounts (Keyser *et al*. 2008). The accumulation of surface woody fuels following wildfire is a function of the decay and fall of fire-killed snags. For example, Russell *et al*. (2006) report within 9 years after fire, an average of 65% of all fire-killed ponderosa pine snags had completely fallen or broken in unsalvaged stands in northern Idaho. This rapid fall of fire-killed trees drives the accumulation of both coarse woody debris (CWD (woody biomass $\geq$7.6 cm diameter)) and fine woody debris

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(FWD (woody biomass <7.6 cm diameter)) following wildfire. Passovoy and Fulé (2006) have shown FWD can approach $\sim 10\,\mathrm{Mg\,ha^{-1}}$ and CWD can reach upwards of $36\,\mathrm{Mg\,ha^{-1}}$ 9 years after fire, which coincides with the time period when the majority of fire-killed ponderosa pine snags fall (Harrington 1996). Coupled with an increase in understorey production following wildfire (e.g. Bataineh *et al.* 2006), elevated FWD loads increase the probability of ignition, thereby increasing fire hazard while high CWD loads increase smoldering combustion and hence potential severity of fire effects on both vegetation and soil (DeBano *et al.* 1998). The anticipated goal of salvage logging, therefore, is to limit the accumulation of these hazardous fuels, especially in stands that experience high rates of overstorey tree mortality, by removing fire-killed snags before they transition from the canopy to surface fuel bed (USDA Forest Service 2000, 2004; Sessions *et al.* 2004).

In forests where timber production is a management objective, whether or not forest stands regenerate following wildfire determines the need for post-fire planting activities. In the Black Hills, the minimum stocking requirement is 370 trees $\mathrm{ha^{-1}}$; however, for timber production, preferred stocking is $\sim$750 trees $\mathrm{ha^{-1}}$ (B. Cook, Black Hills National Forest, pers. comm.). If natural regeneration rates fall short of minimum or preferred stocking levels following wildfire, planting may be required if the primary management objective is to return fire-affected stands to the timber base. The potential for ponderosa pine seedling germination and establishment following wildfire is largely dependent on the availability of a viable seed source and post-fire environmental conditions (Bonnet *et al.* 2005). Abundant seed crops occur in the Black Hills every 2 to 5 years (Boldt and Van Deusen 1974); however, ponderosa pine is heavy-seeded, with a maximum dispersal distance of only 15 to 25 m (Shepperd and Battaglia 2002). Therefore, seed availability following fire is limited to areas that do not experience 100% tree mortality. In ponderosa pine stands that experience stand-replacing fire, no seed trees remain to facilitate regeneration except along the unburned perimeter (Bonnet *et al.* 2005). Consequently, salvage operations that remove fire-killed trees following high-severity fire (e.g. 100% mortality) may not negatively impact the success rate of natural regeneration. However, in forest stands that experience less than stand-replacing fire, salvage logging may hinder natural regeneration. First, harvesting of green trees that could potentially survive (even if fire-damaged) removes seed trees and decreases seed production, which may reduce regeneration potential following fire (Van Nieuwstadt *et al.* 2001; Beschta *et al.* 2004; Lindenmayer and Noss 2006). Second, depending on the timing of salvage operations, physical damage to seedlings (e.g. burial, breakage) caused during logging operations may reduce post-fire seedling density (Donato *et al.* 2006).

Often cited as a negative impact of and argument against post-fire salvage logging is an increased presence of exotic species and a reduction in understorey abundance (e.g. Beschta *et al.* 2004; Lindenmayer and Noss 2006). For example, Purdon *et al.* (2004) found reduced abundance of understorey vegetation following salvage logging in forest stands that had experienced high-severity fire in the boreal forests of southern Québec, whereas Stuart *et al.* (1993) observed reduced abundance of shrubs following post-fire salvage logging in Douglas-fir–hardwood forests of northern California. In contrast, no differences in cover among forbs, grasses, and shrubs were observed by Lopez Ortiz (2007) between salvaged and unsalvaged stands in Douglas-fire forests of Oregon. Little information exists regarding the impacts of salvage logging on understorey recovery in ponderosa pine systems; however, conflicting results (e.g. Stuart *et al.* 1993; Lopez Ortiz 2007) suggest the impacts of salvage logging on understorey vegetation may be site-specific.

As wildfires increase in size and severity throughout the range of ponderosa pine, there is an increased need for science-based information regarding the impacts of post-fire rehabilitation and restoration activities on future forest structure. Despite this need, few controlled studies exist that compare the ecological effects of post-fire salvage logging within the ponderosa pine cover type (McIver and Starr 2001). Recent studies suggest that post-fire salvage logging may reduce successful regeneration and increase fuel loadings and fire hazard in Douglas-fir forests in Oregon (Donato *et al.* 2006). In the present study, we examined whether or not salvage logging has similar effects in ponderosa pine forests of the Black Hills. Specifically, we tested whether salvage logging (i) increases the accumulation of surface fuels; (ii) reduces the establishment of natural regeneration; and (iii) slows the recovery and development of understorey herbaceous and shrub vegetation following a mixed-severity wildfire in the Black Hills, South Dakota.

Methods

Study area

The present study was located within the Jasper Fire perimeter in the Black Hills National Forest, South Dakota, USA (latitudes between 43°42′ and 43°57′N and longitudes between 103°46′ and 104°1′W). The Black Hills are an isolated, forested uplift that extend $\sim$190 km in the north–south direction and $\sim$60–80 km in the east–west direction (Froiland 1990). This dome-shaped uplift rises between $\sim$900 and 1200 m above the surrounding Great Plains in south-western South Dakota and north-eastern Wyoming (Hoffman and Alexander 1987) and forms the easternmost extent of the Rocky Mountains (Froiland 1990). The climate is continental with cold winters and mild, moist summers (Johnson 1949). Mean maximum and minimum daily temperatures range from −3.3° to 13.2°C and yearly precipitation averages $\sim$47 cm, with 65–75% occurring between April and October (Hoffman and Alexander 1987; Froiland 1990; Shepperd and Battaglia 2002).

On 24 August 2000, the Jasper Fire was ignited near the town of Custer in south-western South Dakota. The fire was officially contained on 8 September, 2000 after burning $\sim$34 000 ha or $\sim$7% of the Black Hills National Forest (USDA Forest Service 2000). The Jasper Fire was a mixed-severity fire that produced a combination of surface fire, surface fire with torching (i.e. passive crown fire), and active crown fire that burned through predominantly second-growth ponderosa pine forests. This pattern of fire behavior resulted in a mosaic of forested patches experiencing varying degrees of fire severity within close proximity to one another. Approximately 25% of the landscape burned under low-severity fire (Lentile *et al.* 2005). Sites categorized as low severity experienced, on average, <25% crown

Table 1. Prefire stand structure (live trees ≥5 cm diameter at breast height (DBH)) along with changes in structure due to salvage logging and fire-related tree mortality immediately after fire (fall 2000–late spring 2001) through 2005 and the subsequent 5-year post-fire forest structure (live trees ≥5 cm DBH) in moderate- and high-severity salvaged and unsalvaged sites

Values represent the mean (±1 s.e.). Note: salvage operations were performed between November 2000 and June 2001

	Moderate		High	
	Salvaged	Unsalvaged	Salvaged	Unsalvaged
Density				
Prefire (2000)	358 ± 77	521 ± 59	652 ± 142	757 ± 86
Harvested	130 ± 26	N/A	198 ± 23	N/A
Residual fire-killed trees	191 ± 59	331 ± 44	454 ± 145	757 ± 86
2005	37 ± 17	190 ± 41	0	0
Basal area ($m^2\ ha^{-1}$)				
Prefire (2000)	16.5 ± 2.8	23.0 ± 2.1	25.4 ± 3.1	24.1 ± 1.5
Harvested	10.3 ± 2.2	N/A	15.4 ± 2.1	N/A
Residual fire-killed trees	4.3 ± 1.2	12.4 ± 1.7	10.0 ± 3.1	24.1 ± 1.5
2005	2.0 ± 0.9	10.8 ± 2.0	0	0

scorch with no crown consumption and partial litter and duff consumption with little to no exposure of the bare mineral soil (Keyser *et al.* 2008). Approximately 48% of the landscape burned under moderate-severity fire (Lentile *et al.* 2005). Sites defined as moderate severity experienced >25% crown scorch with partial crown consumption (average crown damage ~75%) and also had the majority of litter and duff consumed (Keyser *et al.* 2008). The remaining 27% of the landscape burned under high-severity, stand-replacing fire (Lentile *et al.* 2005). Sites classified as high severity experienced ~100% crown consumption with complete consumption of the forest floor layer (Keyser *et al.* 2008).

Study sites and sampling design

In the months following the fire and in collaboration with Black Hills National Forest staff, we identified areas that were scheduled for post-fire salvage logging and nearby areas that would be reserved from post-fire management treatments (Keyser *et al.* 2008). Salvage logging was conducted in areas that burned under moderate or high fire severity and were located within timber sales that were active or pending before the Jasper Fire. Any fire-killed timber and any live merchantable tree (e.g. >23 cm DBH) with ≥50% crown scorch and ≥50% bole circumference at root collar charred was designated for removal. Trees were felled with a mechanical feller-buncher and whole trees skidded to a road-side landing with a grapple skidder where they were processed before loading. Logging on all sites was completed between November 2000 and June 2001. Our reserve areas were designated as three ~800-ha units where there was the mixture of low, moderate and high fire severity (Keyser *et al.* 2008).

In June 2001, we randomly established 18 0.3-ha permanent study sites in burned but not logged ponderosa pine stands, and 18 0.3-ha permanent study sites in burned and logged ponderosa pine stands. One-half of the logged and the unlogged study sites were established in stands where fire severity was classified as moderate severity and one-half of the study sites were in stands sites were fire severity was classified as high severity. Unlogged and logged sites were evenly distributed in and adjacent to the three reserve areas. Study sites were mature stands with well-stocked overstories that would typically be included in a commercial timber sale (Table 1).

Data collection

Each study site contained three 0.03-ha overstorey tree subplots located at bearings of 0°, 135°, and 225° 20 m from the site center. In June 2001, before the fall of scorched needles and the onset of post-fire tree growth, we tagged every tree ≥1.4 m in height, recorded species, assessed tree mortality, and measured diameter at breast height (DBH (cm)) in all salvaged and unsalvaged sites. Because we inventoried some of the salvaged sites after harvest operations were complete, information regarding tree mortality 1 year after fire was lacking in moderate-severity salvaged stands. For those trees that were harvested before inventory, we measured stump diameter of all cut stumps within the overstorey tree plots to obtain information regarding prefire stand structure. We converted stump diameter to DBH based on relationships ($R^2 = 0.95$) published by Brown and Cook (2006). In 2005, 5 years after fire, we revisited all salvaged and unsalvaged study sites and assessed tree mortality and remeasured DBH.

Within each site, we sampled both FWD ($Mg\ ha^{-1}$) and CWD ($Mg\ ha^{-1}$) along a 60-m transect that ran 30 m east and 30 m west of each site center using the planar intersect method described by Brown (1974). Fine woody debris was tallied along 10 m of the 60-m transect (5 m east and 5 m west) and CWD was measured along the entire transect 1 (2001) and 5 (2005) years after fire.

We measured ponderosa pine regeneration 2 (2002) and 5 (2005) years after fire using 50 1-m^2 regeneration subplots randomly located throughout each 0.3-ha study site. Within each regeneration subplot, the number of seedlings <1.4 m in height was tallied. To determine whether seedlings germinated after fire or were fire survivors, each seedling was aged by back-counting the bud scale scars from current-year growth. Only seedlings that germinated after fire were included in the analysis. Seedlings were not aged 1 year after fire and therefore not included in the analysis.

We sampled all herbaceous vegetation using six 0.5-m^2 understorey subplots per study site 2 (2002) and 5 (2005) years after fire. Herbaceous vegetation plots were located every 10, 20, and 30 m east and west of a 60-m transect that ran through each site center for a total of six understorey subplots per study site. Within each of the 0.5-m^2 vegetation plots, we visually estimated herbaceous vascular plant cover. Cover of each species was averaged for each study site. Shrubs (woody stems <1.4 m in height) were measured along 40 m of the 60-m transect (20 m east and 20 m west). For each shrub canopy that intersected the transect, we recorded species and distance of canopy intercept (cm). From these data, we calculated average percentage shrub cover for each study site. Owing to time constraints, understorey herbaceous and shrub vegetation were not sampled in salvaged sites 1 year (2001) after fire. Consequently, we report the 2- and 5-year response of herbaceous and shrub vegetation. All understorey vegetation was sampled between late June and early August to control for seasonal changes in understorey composition. All nomenclature as well as native and non-native status of herbaceous and shrub species follows the United States Department of Agriculture, National Resources Conservation Service (USDA NRCS) PLANTS database (USDA NRCS 2006).

Data analysis

We used an analysis of variance (ANOVA) with repeated-measures to determine the effects of fire severity (moderate and high), salvage treatment (salvaged and unsalvaged), time (1 (or 2) and 5 years after fire), and their interactions on FWD and CWD, post-fire tree regeneration, total plant cover, exotic plant cover, and relative abundance of plant functional groups (e.g. shrubs, forbs, and grasses). In all analyses, site was included as a random variable and fire severity, salvage treatment, and time were fixed variables. Following significant *F*-tests in the repeated-measures analysis, pairwise comparisons were performed among treatments using Fisher's protected least significant difference (l.s.d.) procedure. Owing to the limited number of *a priori* comparisons, no adjustments were made to the l.s.d. multiple comparison procedure. Response variables were $\log_e$-transformed, $\sqrt{}$transformed, or $\sqrt{}$arc sin transformed when necessary to approximate normality and homoscedasticity (Steel *et al.* 1997). The means and standard errors we report are from the raw, untransformed data. All analyses were performed using *SAS v. 9.1* (SAS Institute 2005) and were significant at the 0.05 level.

Results

Salvage logging and fire-related tree mortality substantially altered post-fire forest structure. Salvage logging removed fire-killed and fire-damaged large trees but left lightly damaged large trees and small fire-killed trees. Salvage logging removed, on average, 130 trees ha^{-1} (10.3 m^2 ha^{-1} basal area, BA) from moderately burned, salvaged sites (Table 1). Between 2000 and 2005, an additional 191 trees ha^{-1} (4.3 m^2 ha^{-1} BA) were either immediately killed via fire or experienced delayed fire-related tree mortality, resulting in only 37 live trees ha^{-1} (2.0 m^2 ha^{-1} BA) 5 years after fire. In moderately burned, unsalvaged sites, fire-related mortality of 331 trees ha^{-1} (12.4 m^2 ha^{-1} BA) between 2000 and 2005 reduced stand density to 190 live trees ha^{-1} and 10.8 m^2 ha^{-1} BA 5 years after fire. In high-severity salvaged and unsalvaged sites, 100% mortality occurred. During salvage operations, 30% of the average prefire stand density or 61% of the average stand BA was harvested in salvaged sites.

Salvage treatment significantly influenced FWD and CWD loads, but the effects of salvage treatment on both FWD ($F = 12.8$, d.f. = 1, 32, $P = 0.0011$) and CWD ($F = 24.3$, d.f. = 1, 32, $P < 0.0001$) loading varied within individual years. One year after fire and following salvage logging, FWD and CWD loadings were significantly higher on salvaged than on unsalvaged sites (Table 2). However, in all cases FWD and CWD were low, averaging ~6 Mg ha^{-1} for salvaged sites and substantially less on unsalvaged sites. Five years after fire, FWD had increased to moderate levels of ~13 Mg ha^{-1}, and was equal on salvaged and unsalvaged sites. Coarse woody debris increased over time on both salvaged and unsalvaged sites, and was significantly greater on unsalvaged sites at ~25 Mg ha^{-1} than on salvaged sites at ~16 Mg ha^{-1}. Only 55% of dead trees had fallen 5 years after fire, so it is likely these differences will increase over time, because the remaining standing fire-killed tree biomass is much higher on unsalvaged than salvaged sites owing to harvesting.

Salvage treatment significantly influenced post-fire regeneration; however, the effect of salvage varied with fire severity ($F = 23.2$, d.f. = 1, 30, $P < 0.0001$). Five years after fire, regeneration averaged ~350 seedlings ha^{-1} in moderately burned salvaged sites compared with ~1400 seedlings ha^{-1} in moderately burned unsalvaged sites (Fig. 1). Regeneration was low in high-severity sites regardless of salvage treatment and time since fire. After 5 years, high-severity salvaged sites, however, contained an average of ~225 more seedlings ha^{-1} than unsalvaged sites.

Salvage treatment did not significantly affect the recovery of understorey plant cover ($P > 0.05$). Cover in moderate- and high-severity salvaged and unsalvaged sites averaged 40% (±4.4) 2 years after fire and increased to 75% (±4.6) 5 years after fire. The rapid recovery of plant cover in salvaged and unsalvaged sites included an increase in exotic plant cover although exotic plant cover did not differ between salvaged and unsalvaged sites ($P > 0.05$). On average, exotic cover was 5% (±1.3) in moderate- and high-severity salvaged and unsalvaged 2 years after fire and ~17% (±3.1) after 5 years.

Although salvage treatment and fire severity did not influence total plant cover, the recovery of functional groups (e.g. grasses, shrubs, and forbs) did vary with salvage treatment. Forb ($F = 37.7$, d.f. = 1, 32, $P < 0.0001$) and grass cover ($F = 10.6$,

Table 2. Surface woody fuel loadings (Mg ha^{-1}) for fine woody debris (FWD) and coarse woody debris (CWD) within salvaged and unsalvaged sites 1 (2001) and 5 (2005) years following the Jasper Fire

Comparisons were performed following a significant salvage × year interaction in the repeated-measured ANOVA ($P < 0.01$). Values represent the mean (±1 s.e.) averaged over moderate and high fire severities. Means followed by the same letter are not significantly different within a given year

	FWD (Mg ha^{-1})		CWD (Mg ha^{-1})	
	2001	2005	2001	2005
Salvaged	6.3 (1.3)^a	13.3 (1.6)^a	6.5 (1.5)^a	16.2 (3.1)^a
Unsalvaged	0.9 (0.2)^b	13.3 (1.9)^a	2.3 (0.8)^b	24.9 (3.2)^b

d.f. = 1, 32, $P = 0.0027$) were significantly influenced by salvage treatment but the effects varied over individual years. Two years after fire, forb cover was 27% in unsalvaged sites and only 7% in salvaged sites (Fig. 2*a*). After 5 years, however, forb cover was similar in salvaged sites and unsalvaged sites. In contrast to forbs, grass cover was greater on salvaged sites than unsalvaged sites 2 years after fire (Fig. 2*b*). Five years after fire, however, grass cover increased in unsalvaged sites and was similar to cover observed in salvaged sites. Shrub cover responded differently to the salvage treatments depending on fire severity and time since fire ($F = 4.7$, d.f. = 1, 32, $P = 0.0385$). In moderately burned salvaged and unsalvaged sites, no difference in shrub cover was observed throughout the study, with shrub cover averaging ~10% (Fig. 3*a*). Although shrub cover in high-severity salvaged sites was lower than in unsalvaged sites 2 years after fire, after 5 years, we observed no differences between the salvage treatments (Fig. 3*b*).

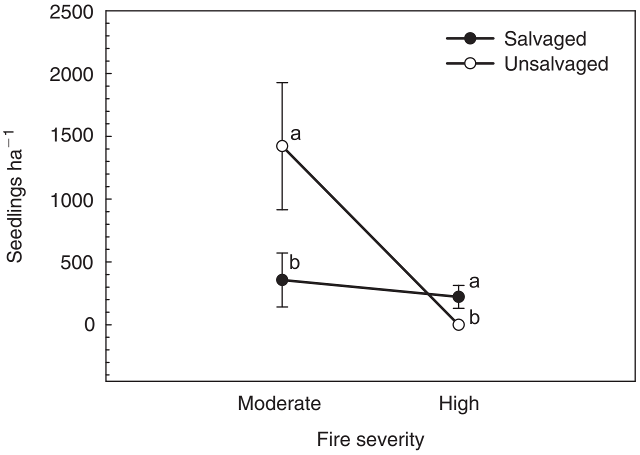

Fig. 1. Post-fire regeneration density (seedlings ha^{-1}) in salvaged and unsalvaged moderate- and high-severity sites. Comparisons were performed following a significant salvage × severity interaction in the repeated-measures ANOVA ($P < 0.0001$). Data presented are from 5 (2005) years after fire and are indicative of the aggregate effects of salvage treatment and fire severity on post-fire regeneration. Values represent the mean ± 1 s.e. Means followed by the same letter within a fire severity class are not significantly different.

Discussion

Recent work in the north-west United States suggests that salvage logging 2 to 3 years after fire increases surface fuel loads, fire hazard, and causes a decrease in regeneration potential (Donato *et al.* 2006). Our results, although specific to ponderosa pine stands burned by the Jasper Fire and subsequently salvaged in the Black Hills, do not confirm these observations and suggest that the specifics of forest type and fire severity along with the timing and methods used during salvage operations need to be considered when evaluating secondary effects of salvage logging beyond recovery of economic tree value. Following the Jasper Fire, salvage logging was conducted in stands affected by two types of fire severity – moderate, where surface and passive crown fire caused <40% initial overstorey tree mortality, and severe, where active crown fire caused complete tree mortality over large contiguous areas. Salvage logging occurred quickly and was completed within the first year after fire. Marking guidelines for salvage operations specified that any fire-killed or any live merchantable tree >23 cm DBH with ≥50% crown scorch and ≥50% of the bole circumference at the root collar charred could be harvested. All salvage logging was performed using whole-tree harvesting methods where trees were felled with a mechanical feller-buncher and whole trees skidded to landing areas with grapple skidders where they were processed before loading.

One year following the Jasper Fire, FWD and CWD loads were low in moderately and severely burned salvaged and unsalvaged sites owing to fuel consumption, clean logging practices,

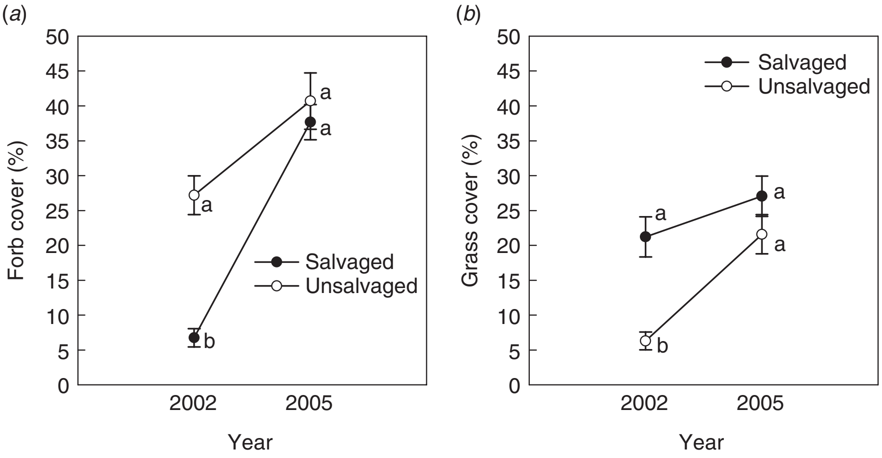

Fig. 2. Forb (*a*) and grass cover (%) (*b*) in salvaged and unsalvaged sites 2 (2002) and 5 (2005) years after fire. Comparisons of lsmeans were performed following significant salvage × severity interactions in the repeated-measures ANOVA ($P < 0.01$). Values represent the mean, averaged over moderate and high fire severities, ±1 s.e. Means followed by the same letter are not significantly different within a given year.

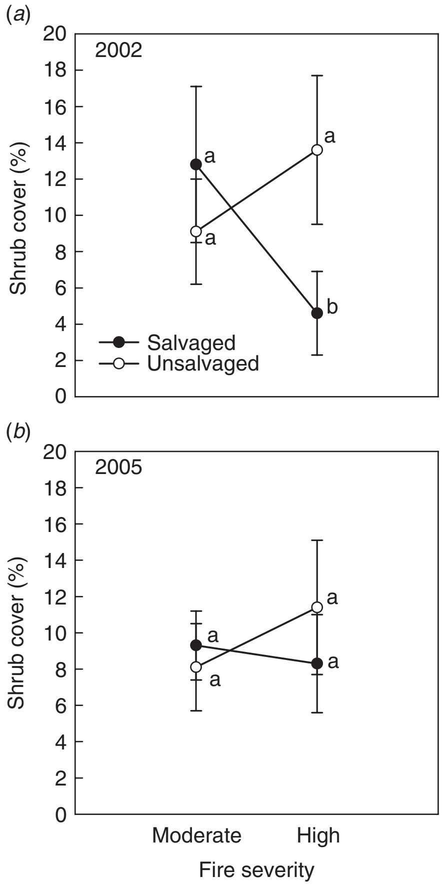

Fig. 3. Shrub cover (%) in moderate- and high-severity salvaged and unsalvaged sites 2 (2002) (*a*) and 5 (2005) (*b*) years after fire. Comparisons of lsmeans were performed following a significant salvage × severity × year interaction in the repeated-measures ANOVA ($P < 0.05$). Values represent the mean ± 1 s.e. Means followed by the same letter within a fire severity class are not significantly different.

and the lack of snag-fall during this time (Table 2). Fuel loads following the Jasper Fire were not static, as surface fuel accumulated differentially within salvaged and unsalvaged sites between 1 and 5 years after fire. The harvesting of immediate and delayed large-tree mortality in salvaged sites limited CWD accumulation to 16 Mg ha^{-1}, as relatively few large, fire-killed trees remained following salvage operations. Fine fuels, however, increased 110% in salvaged sites over this time period as smaller fire-killed trees left during harvest operations fell. In unsalvaged areas, dead canopy fuels resulting from fire-related mortality (Keyser *et al.* 2006) created a large pool of potential surface fuel. After 5 years, an average of 55% of all fire-killed trees $\geq$10 cm DBH had fallen in unsalvaged sites, leading to a 10-fold increase in CWD and 14-fold increase in FWD. Additional increases in both FWD and CWD can be expected as significant snag-fall has been shown to occur through the ninth year after fire (Passovoy and Fulé 2006). Although the rates of CWD accumulation between 1 and 5 years after fire were well over 100% in both salvaged and unsalvaged sites, total CWD loads were within the ~15 to 30 Mg ha^{-1} range recommended by Graham *et al.* (1994) and the ~11 to 45 Mg ha^{-1} range recommended by Brown *et al.* (2003) for maintaining long-term site productivity as well as other ecosystem services (e.g. wildlife habitat). With respect to CWD input, therefore, salvage logging following the Jasper Fire did not likely reduce potential site productivity or potential wildlife habitat in our study sites. As surface fuels increase and approach the upper limits of the recommended ranges (e.g. Graham *et al.* 1994; Brown *et al.* 2003), providing for ecosystem services such as site productivity and wildlife habitat may conflict with fuels reduction efforts and the need for managers to reduce fire hazard and potential fire severity. Fire behavior is dependent on multiple factors including, but not limited to, fuel load, fuel continuity, fuel moisture, and weather (DeBano *et al.* 1998). High FWD loads increase fire hazard by increasing the probability of ignition, fireline intensity, flame height, and rate of spread (Rothermel 1972; Schroeder *et al.* 2006). Although CWD does not directly impact fire hazard, it does contribute to smoldering combustion, which can exacerbate both cambial and root damage (DeBano *et al.* 1998), both of which have been shown to greatly increase the probability of tree mortality (Ryan *et al.* 1988; Swezy and Agee 1991; Stephens and Finney 2002).

Most of the regeneration that existed before the Jasper Fire was killed directly by the fire in all study sites. Salvage logging that occurred immediately after fire was performed before any post-fire germination. Therefore, in contrast to Donato *et al.* (2006) who reported that salvage logging 2 to 3 years after fire resulted in physical damage and significant mortality of natural regeneration, harvest operations that occurred during the immediate months following the Jasper Fire had no direct impact on post-fire seedling survival. The most substantial impact of salvage logging on post-fire regeneration potential was the impact on seed source availability. In moderate-severity salvaged sites, the salvage prescriptions left a sparse overstorey of seed-producing ponderosa pine trees ($\leq$2 m^2 ha^{-1} residual BA; Table 1), which resulted in relatively low regeneration success (Fig. 1). In contrast, after 5 years of fire-related tree mortality, ~10 m^2 ha^{-1} of seed-producing overstorey trees remained in moderate-severity unsalvaged sites, which, when coupled with the ground disturbance, led to successful ponderosa pine regeneration in moderate-severity sites despite drought conditions throughout the five growing seasons after fire. The ample regeneration we observed in moderate-severity unsalvaged sites suggests a reexamination of the rules used in the Black Hills to identify trees for post-fire salvage removal. In the future, leaving a greater proportion of large-diameter fire-damaged trees that have a high probability of survival (Keyser *et al.* 2006) will provide for future seed production and increase the success of natural regeneration following salvage operations. Regardless of salvage treatment, Keyser *et al.* (2008) suggest that low residual overstorey density along with increased light transmittance in moderate-severity sites will promote overstorey recruitment of post-fire seedlings and ultimately result in the development of a multi-storied forest structure. In high-severity sites, salvage logging did not substantially impact natural regeneration because much of the severely burned areas are beyond seed-fall range of ponderosa pine (Shepperd and Battaglia 2002; Lentile *et al.* 2005). Although regeneration in high-severity sites was statistically higher in unsalvaged sites, neither the high-severity salvaged nor unsalvaged sites met minimum stocking levels for timber management objectives in the Black Hills. Regardless of salvage treatment, if management objectives include a return to the timber base, planting may be the only effective way to secure timely regeneration of ponderosa pine on these high-severity sites in both salvaged and unsalvaged sites. In contrast, Keyser *et al.* (2008) suggest that if management objectives in these understocked, high-severity sites include maintaining newly created wildlife habitat and increasing biodiversity, no direct planting would be necessary, as limiting planting efforts in these stands would provide for increased structural heterogeneity within the relatively homogeneous surrounding landscape.

In the Black Hills ponderosa pine system, we found no discernable effect of salvage logging on understorey development 5 years following the Jasper Fire. There was no indication that salvage logging alone caused a reduction in total plant cover or an increase in the abundance of exotic species. In addition, any differences in the distribution of functional groups between salvaged and unsalvaged sites that were observed within the initial years following the Jasper Fire were not observed 5 years after fire (Figs 2, 3). This is contrary to results published by Stuart *et al.* (1993), who report a decrease in shrub cover following post-fire salvage operations in northern California. The rapid recovery of the shrub layer was largely due to an increase in cover by shrubs capable of sprouting following fire, including mountain ninebark (*Physocarpus monogynus*), kinnikinnick (*Arctostaphylos uva-ursi*), and Orgeon grape (*Mahonia repens*) in moderate-severity sites and western snowberry (*Symphoricarpos occidentalis*) and mountain ninebark in high-severity sites. Regardless of salvage treatment, the understories of both moderately and severely burned sites were dominated by forbs and grasses after 5 years. Increased post-fire nitrogen availability (Keyser *et al.* 2008) and high mortality rates in the unsalvaged sites coupled with harvesting of both live and dead trees in salvaged sites likely reduced aboveground competition for light and belowground competition for nutrients and water, which, over 5 years, promoted an increase in cover of grass and forb species (Riegel *et al.* 1992, 1995).

Conclusion

Our results are applicable to ponderosa pine stands salvaged following the Jasper Fire in the Black Hills. Compared with recent studies (e.g. Donato *et al.* 2006), our results suggest that the effects of salvage logging may be dependent on when and how salvage logging is conducted as well as forest type rather than an invariant set of effects inherent to salvage logging. Data from the present study suggest the timely removal (e.g. within 1 year after fire) of dead and dying trees can reduce future surface fuels compared with unlogged areas, depending on how the logging is conducted. For example, whole-tree harvesting systems, where processing occurs off-site, reduced residual dead tree biomass following the Jasper Fire. However, hand-felling and within-stand bucking and limbing where residual biomass is left on-site may result in an increase in FWD. Regeneration can be reduced by physical damage from salvage logging if salvage logging is delayed until natural regeneration has occurred (Donato *et al.* 2006) or if salvage logging includes substantial removal of live trees that reduces seed availability. However, timely salvage before post-fire seed germination that leaves sufficient seed source may have little impact on post-fire regeneration success or failure. Assessing the potential impacts of salvage logging should be conducted on a site-specific basis, integrating ecology, silviculture, and harvest systems. Further research comparing the effects of salvage logging on fuel accumulation, regeneration potential, and understorey vegetation across forest types and harvesting systems is required to assess whether the results we present in the present paper are applicable elsewhere.

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