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The efficacy of salvage logging in reducing subsequent fire severity in conifer-dominated forests of Minnesota, USA

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Abstract. Although primarily used to mitigate economic losses following disturbance, salvage logging has also been justified on the basis of reducing fire risk and fire severity; however, its ability to achieve these secondary objectives remains unclear. The patchiness resulting from a sequence of recent disturbances—blowdown, salvage logging, and wildfire—provided an excellent opportunity to assess the impacts of blowdown and salvage logging on wildfire severity. We used two fire-severity assessments (tree-crown and forest-floor characteristics) to compare post-wildfire conditions among three treatment combinations (Blowdown–Salvage–Fire, Blowdown–Fire, and Fire only). Our results suggest that salvage logging reduced the intensity (heat released) of the subsequent fire. However, its effect on severity (impact to the system) differed between the tree crowns and forest floor: tree-crown indices suggest that salvage logging decreased fire severity (albeit with modest statistical support), while forest-floor indices suggest that salvage logging increased fire severity. We attribute the latter finding to the greater exposure of mineral soil caused by logging operations; once exposed, soils are more likely to register the damaging effects of fire, even if fire intensity is not extreme. These results highlight the important distinction between fire intensity and severity when formulating post-disturbance management prescriptions.

Key words: blowdown; fire behavior; fuel reduction treatments; Ham Lake fire; multiple disturbances; Pinus banksiana*; Superior National Forest, Minnesota, USA; wildfire intensity.*

Communications

Introduction

Wildfire activity in forests of North America and elsewhere has increased markedly in recent decades (Agee and Skinner 2005, Westerling et al. 2006, Flannigan et al. 2009). Controversies surrounding management practices, such as salvage logging (harvesting following natural disturbance), have similarly increased during this time (Lindenmayer et al. 2004). Although primarily used to mitigate economic losses following major disturbance, salvage logging has also been justified on the basis of reducing fire risk as well as promoting forest regeneration (Sessions et al. 2004). However, its ability to achieve these secondary objectives remains poorly understood (Lindenmayer et al. 2004, Greene et al. 2006). Depending on how it is conducted, salvage logging may increase fuel loads (Donato et al. 2006), impede successful natural regeneration (Van Nieuwstadt et al. 2001, Donato et al. 2006), and alter the rate and trajectory of forest recovery (Lindenmayer and Ough 2006, Palik and Kastendick 2009).

Few studies have addressed the efficacy of salvage logging in reducing subsequent wildfire severity (but see Kulakowski and Veblen 2007, Thompson et al. 2007, Thompson and Spies 2010). Nevertheless, understanding the ecological consequences of this disturbance sequence is critical to resolving the growing international debate over salvage logging (Lindenmayer et al. 2004, Dellasala et al. 2006), as well as the general concern that multiple disturbances occurring in rapid sequence may create novel ecosystem responses, causing dramatic shifts in natural communities (Paine et al. 1998).

A rare sequence of disturbances allowed us to evaluate the impact of blowdown and salvage logging on the severity of a subsequent wildfire. In July 1999 a severe windstorm affected nearly 200,000 ha of forest in northern Minnesota, USA. Between 1999 and 2002, fuel reduction treatments, including salvage logging, were conducted in portions of the blowdown area. Then in May 2007 a large wildfire burned through much of this area. The patchiness of these disturbances created three treatment combinations: Blowdown–Salvage–Fire,

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TABLE 1. Disturbance combinations (i.e., treatments) examined in the Superior National Forest, northern Minnesota, USA.

Treatment	No. sites	No. plots	1999 blowdown	Salvage logging	2007 wildfire
Blowdown–salvage–fire	6	59	yes	yes	yes
Blowdown–fire	6	64	yes	no	yes
Fire only	6	63	no	no	yes

Note: Plots were circular, 200 m^2 in area, and separated by 40 m.

Blowdown–Fire, Fire only (Table 1), providing an excellent opportunity to assess the impacts of blowdown and salvage logging (singly and in combination) on subsequent wildfire severity. A previous study (pre-wildfire) in this same landscape documented that salvage logging reduced fine and coarse fuels in the blowdown area (Gilmore et al. 2003). Given the assumption that fire behavior and severity are positively linked to fuel loads (Schoennagel et al. 2004, Knapp et al. 2007), we hypothesized that post-blowdown salvage logging would reduce the intensity and severity of the ensuing wildfire. Our objective was to test this hypothesis using field-based assessments of fire intensity and severity in the various disturbance combinations. We assessed severity using a newly developed method that produces two indices, one based on characteristics of tree crowns and another based on the forest floor (Jain and Graham 2007).

A number of authors have highlighted problems arising from inconsistent and unclear use of fire-science terminology (Lentile et al. 2006, Keely 2009). In an attempt to clarify terms, Keely (2009) recognizes the categories "burn severity," "fire severity," and "fire intensity," and provides numerous descriptors within each. Though not assessed in this paper, *burn severity* refers to the loss of surface organic matter, determined by remote-sensing applications. For the purpose of this paper, and following Keely (2009), Lentile et al. (2006), and Pickett and White (1985), we define *fire intensity* as the physical force (heat released by combustion) and *fire severity* as the impact to the ecosystem. The distinction between fire intensity and severity is critical because the two are not always correlated (Lentile et al. 2006). Further, Jain and Graham (2007) introduced the concept of the fire continuum, which includes the pre-fire environment, fire characteristics, and the post-fire environment. In this context, our severity indices characterize the post-fire environment, and hence a site's ability to maintain productivity and allow timely recolonization by forest vegetation. By focusing on the post-fire environment, we believe that our fire-severity assessment, as opposed to a fire-intensity assessment, is more appropriate for most forest-management applications (Lentile et al. 2006, Jain and Graham 2007).

MATERIALS AND METHODS

Study area and background

The study was conducted within the Gunflint Corridor of the Superior National Forest, Minnesota, USA (Fig. 1). This area has a mean annual precipitation of ~71 cm and a mean temperature of 2°C, with mean July and January temperatures of 17°C and −8°C, respectively. Soils are characterized by glacial tills, outwash, and lacustrine deposits (USDA Forest Service 2000). The study area was dominated by mature *Pinus banksiana* (jack pine) prior to the series of disturbances described below. This forest type is considered fire dependent, with an average fire return interval of 50–75 years prior to EuroAmerican settlement (Heinselman 1996).

On 4 July 1999 severe thunderstorm downbursts damaged nearly 200,000 ha of forest in Minnesota, including large areas within the Superior National Forest and the adjacent Gunflint Corridor (Fig. 1). Between 1999 and 2002, salvage logging was conducted to reduce both fuel loads and fire risk (USDA Forest Service 2000). On five of the six salvaged sites used in this study (see *Field sampling*, below), harvesting operations took place during the frost- and snow-free period using conventional, ground-based equipment, including a tracked feller-buncher and rubber-tired grapple skidder. Also on five of the six salvaged sites, harvest slash was removed to a landing where it was burned (T. Norman, *personal communication*); we assume slash was similarly removed from the sixth site given the intent of the harvests. In May 2007 the Ham Lake fire burned ~14 800 ha within the Superior National Forest and Gunflint Corridor including areas that had been blowndown and salvage logged (Fig. 1). The spatial location of fire-suppression activities (largely aircraft water drops) are unknown, but most likely targeted the wildland–urban interface, many kilometers from our study sites. Finally, although prescribed burning was also undertaken as a fuel-reduction treatment, the treated areas were small and few in number relative to natural features such as lakes, streams, marshes, bogs, and local topography that affect landscape-level fire behavior. Thus, we believe the presence of these burns had little or no bearing on our results.

Field sampling and severity assessment

Each of our three disturbance combinations (henceforth "treatments"; Table 1) included six replicate sites; each site included at least six (depending on site size) 200-m^2 circular plots on a regular grid that emanated from a random initial starting location. Plots were separated by 40 m, and the area covered by the grid network was ~2.6

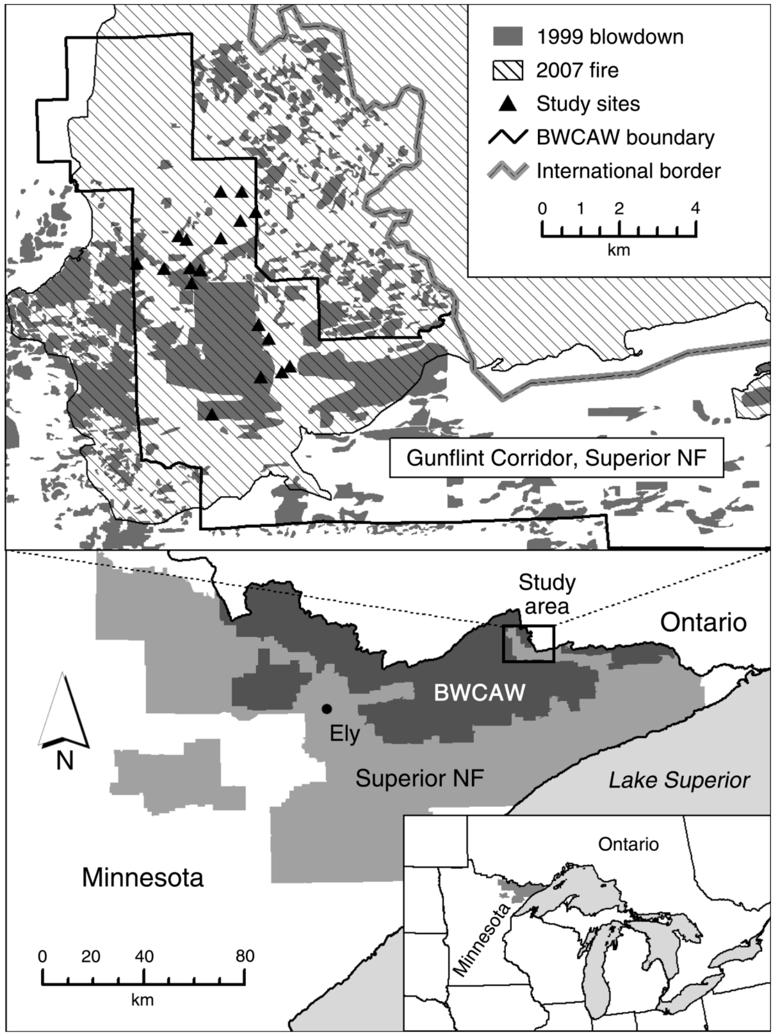

FIG. 1. Location of study sites and disturbed areas in *Pinus banksiana* forests within the Gunflint Corridor of Superior National Forest (NF) of northeastern Minnesota, USA. BWCAW refers to the Boundary Waters Canoe Area Wilderness.

ha per site. A total of 186 plots were thus inventoried on the 18 sites (Table 1, Fig. 1). Included in these 18 sites are 8 sites previously established by Gilmore et al. (2003), who examined fuel loads following the 1999 blowdown. The remaining 10 sites were selected using a GIS to identify all potential sites, followed by random selection. Randomly selected sites were ground-truthed for mature *P. banksiana* dominance and adherence to the expected disturbance treatment. Sites serve as the experimental units in analyses, and plots (within sites) serve as the sampling units.

Fire severity was assessed following Jain and Graham (2007), whose method results in two severity indices for each plot, one characterizing tree crowns and one characterizing the forest floor (Appendix), as impact to these two strata can differ dramatically for a given site (Halofsky and Hibbs 2009). The tree-crown severity index is based on the color of conifer foliage along a gradient from green to black. Tree-crown severity assessment was possible even on salvage-logged sites because enough trees remained to allow this assessment. The forest-floor severity index is based on percent cover, visually assessed, for total organic forest floor present (litter [Oi horizon] plus duff [Oe, Oa], henceforth referred to as "litter"), unburned mineral soil, black-charred soil, grey-charred soil, and orange-stained soil. Data on woody-debris charring, recorded in four classes ranging from unburned to severely burned, were used in the rare cases of ties within the key based on litter and soil characteristics.

In addition to our fire-severity indices, we include one measure of fire intensity, namely scorch-height, assuming greater heights represent greater intensity (Van Wagner 1973, Hély et al. 2003). We recorded scorch height as the highest point of charring on tree boles, measured on the uphill side in cases where relief warranted doing so. Scorch heights were averaged per plot. All field sampling was conducted in May 2008.

Data analyses

Because our fire severity data were categorical (i.e., severity classes), we used generalized linear mixed-model multinomial logistic regressions via PROC GLIMMIX in SAS/STAT software (SAS Institute 2008), using a multinomial distribution and a cumulative logit link function with the Kenward-Rogers adjustment for denominator degrees of freedom. We employed this model for both the tree-crown and forest-floor severity data to test if the three treatments (Blowdown–Salvage–Fire, Blowdown–Fire, Fire only; Table 1) differed with respect to the distribution of plots among fire-severity classes. Treatment was the fixed effect in these models, and site and plot-within-site were the random effects. Because LSMEANS are not available with the multinomial distribution, our models included contrast statements to assess which treatments differed from others. Because of very few observations in the lowest classes for the tree-crown severity data, we collapsed classes A–E into one class (labeled "E") prior to analyses (see Appendix). Similarly, we collapsed forest-floor classes A and B into one class (labeled "B") and classes F–I into one class (labeled "F") (see Appendix). After collapsing, both data sets contained five classes with adequate observations in each.

Because the scorch-height data were not normally distributed, we used PROC GLIMMIX in SAS/STAT software (SAS Institute 2008) with a gamma distribution and log link function to test for differences in scorch height among treatments. As above, this analysis was treated as a generalized linear mixed model, with treatment as the fixed effect, and site as the random effect. We used the Kenward-Rogers adjustment for denominator degrees of freedom, and we used linear contrasts to test for differences between specific treatment combinations. P values ≤ 0.05 were taken to be statistically significant in all tests.

Results

Pairwise comparisons from the generalized linear mixed-model multinomial logistic regressions indicate that the Blowdown–Fire treatment experienced greater tree-crown severity than did the Fire-only treatment (model $P = 0.017$, linear contrast $P = 0.005$). No other pairwise comparisons differed significantly (Blowdown–Salvage–Fire vs. Blowdown–Fire, $P = 0.064$; Blowdown–Salvage–Fire vs. Fire only, $P = 0.174$) (Fig. 2). Thus, with respect to the tree-crown severity assessment, the salvage treatment was intermediate between the other two, yet not differing significantly from either. In contrast to the tree-crown severity results, pairwise comparisons from the forest-floor severity regressions indicate that the Blowdown–Salvage–Fire treatment had higher severity than the other two treatments (model $P = 0.003$; linear contrast P values < 0.013), which did not differ from one another ($P = 0.194$) (Fig. 2). Thus, with respect to the forest-floor assessment of severity, salvage logging increased fire severity relative to the other treatments.

Results from the scorch-height analysis revealed that the Blowdown–Salvage–Fire had significantly lower scorch heights than the other two treatments (model $P = 0.0001$; linear contrast P values < 0.0002), which did not differ from each other (linear contrast $P = 0.784$).

Discussion

Although salvage logging clearly meets its primary objective of mitigating economic losses from damaged timber, its ability to achieve other objectives has not been extensively tested. In particular, its efficacy in reducing subsequent fire severity has been called into question (Donato et al. 2006, Thompson et al. 2007). To date, few studies have addressed the effects of salvage logging on subsequent fire severity (but see Kulakowski and Veblen 2007, Thompson et al. 2007, Thompson and Spies 2010). Ours is the first to use field data, as opposed to remotely sensed data or aerial photographs, to address this issue. This is an important distinction, considering that remotely sensed measures of fire severity may not correlate well with ground-based assessments (Halofsky and Hibbs 2009, De Santis and Chuvieco 2009), and various remotely sensed measures may differ from one another in their abilities to assess burn severity (De Santis and Chuvieco 2009).

Our tree-crown severity assessment indicated that the Blowdown–Fire treatment registered greater severity than did the Fire-only treatment, with the Blowdown–Salvage–Fire treatment being intermediate between the two, yet not differing significantly from either. However, inspection of the P values from pairwise tests (see *Results*, above) suggests that salvage logging produced tree-crown severities more closely resembling those of the Fire-only treatment (lowest severity) than those of the Blowdown–Fire treatment (highest severity). Indeed, plot distributions for the Blowdown–Salvage–Fire and Fire only treatments are quite similar in the three highest tree-crown severity classes (Fig. 2). Given the positive relationship between fuel loads and fire severity (Schoennagel et al. 2004, Knapp et al. 2007), the shift toward lower severity in the salvaged area could be explained by the fact that both coarse fuels (merchantable material) and fine fuels (slash) had been removed during logging operations. Following this reasoning, these results lend support (albeit with modest statistical evidence) for our hypothesis that salvage logging would reduce tree-crown severity in a subsequent fire. This conclusion was corroborated to some extent by a report from USDA Forest Service's Fire Behavior Assessment Team (Fites et al. 2007) who concluded that fuel reduction treatments reduced fire severity in blowdown areas in this same fire. However, these results are not directly comparable to ours because salvage treatments were combined with prescribed burning and other fuel reduction treatments, precluding a direct assessment of salvage logging. We note that the tree-crown severity

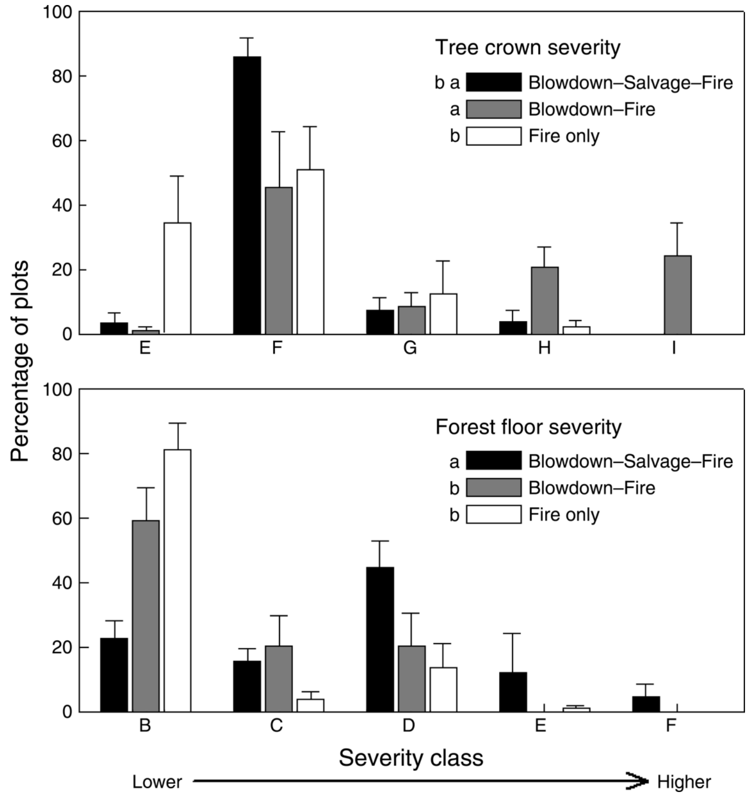

FIG. 2. Distribution of plots among the five fire-severity classes for each of the three disturbance combinations (i.e., treatments; data are means + SE). Scales of tree-crown and forest-floor severity classes are independent (see Appendix for class descriptions). Treatment combinations with different lowercase letters, shown beside the treatment key, are significantly different at $\alpha < 0.05$.

classes registered here correspond to rather high percentage crown scorches (Appendix), suggesting significant future mortality risk even for the Blowdown–Salvage–Fire and Fire only treatments (see Peterson and Arbaugh 1986, Ryan and Reinhardt 1988).

However, our forest-floor severity assessment showed that the Blowdown–Salvage–Fire treatment registered greater fire severity than did the other two treatments. This result can be seen in Fig. 2, which shows a greater percentage of Blowdown–Salvage–Fire plots in the three highest forest-floor severity classes. Thus, in contrast to the tree-crown assessment, salvage logging within the blowdown increased fire severity. This finding did not support our hypothesis that salvage logging would reduce forest-floor severity in a subsequent fire. An explanation hinges on the distinction between fire intensity (heat released) and severity (impact to the ecosystem) (Lentile et al. 2006, Keely 2009). Although salvage logging may at times increase fine and coarse fuel loads (Donato et al. 2006), this was not the case in our study because the salvage objectives specifically included fuel reduction. Gilmore et al. (2003) report from this same landscape that salvage operations reduced both fine and coarse fuel loads. We believe that these lower fuel loads reduced the intensity of the subsequent fire. Indeed, the Blowdown–Salvage–Fire treatment had the lowest scorch heights (a proxy for fire intensity; Van Wagner 1973, Hély et al. 2003) of the three treatments. Yet despite lower intensity, fire in the salvaged areas caused the greatest impact to the forest floor. This finding can partially be explained by greater disruption and exposure of mineral soil caused by harvesting equipment (S. Fraver, *personal observation*); once exposed, soils are more likely to register the damaging effects of fire, even if fire intensity is not extreme. Alterations to the litter may also play a role, as compaction by harvesting equipment could enhance smoldering combustion, thereby contributing to deeper heat transfer to soils (DeBano et al. 1998). Further, the more open salvaged sites were likely drier, relative to the other sites, suggesting greater litter consumption at a given fire intensity (Van Wagner 1972). The results of these processes would be registered as greater fire severity using our forest-floor assessment. Similar forest-floor disruptions by salvage operations have been previously reported (Purdon et al. 2004, Greene et al. 2006). We note that even the highest forest-floor severity classes registered here retained some leaf litter and had mineral soils showing only black char or grey (not orange; Appendix), suggesting that surface soils did not undergo pronounced physical alterations, such as increased water repellency, pH, and bulk density

(Certini 2005). Such alterations would be manifest by the complete loss of litter and orange-red mineral soil coloration (Ulery and Graham 1993).

Conclusions and management implications

Our results suggest that salvage logging reduced the intensity (heat released) of the subsequent fire, presumably because both coarse and fine fuels had been removed at harvest. However, its effect on severity (impact to the system) differed between the tree-crown and forest-floor assessments. Lower fire intensity in the salvaged areas translated to lower tree-crown severity (albeit with modest statistical evidence), yet, perhaps counterintuitively, higher forest-floor severity. The latter finding may be attributed to forest-floor alterations by harvesting equipment, which made the forest floor more susceptible to damage from heating. These results point to the importance of considering multiple criteria (here tree crown and forest floor), as well as details of the salvage operation (e.g., timing, equipment used, and amount of fuels left on site) when evaluating the ecological consequences of salvage logging (Greene et al. 2006, Keyser et al. 2009). In particular, the harvesting equipment used dictates the amount of forest-floor disturbance (Greene et al. 2006), and the amount of slash remaining on-site post-salvage determines fire hazard, given that these fine fuels largely govern ignition, spread rate, and fire-line intensity (Dodge 1972, Rothermel 1972).

In sum, our results do not provide unequivocal evidence that salvage logging reduced severity of a subsequent fire. To facilitate comparisons with other studies, we provide details on the timing of salvage operations (primarily unfrozen and snow-free ground conditions), type of equipment used (largely tracked equipment), and treatment of slash (removed from site for disposal). Without considering these details, and the attendant ranges of ecological consequences, it may remain difficult to formulate guidelines—including doing nothing—regarding post-disturbance forest management. Given the large economic and fuel reduction incentives afforded by salvage logging, the practice will likely continue; in the absence of adequate guidelines, it may continue haphazardly.

Finally, our results clearly highlight the importance of distinguishing between fire intensity and fire severity when gauging the efficacy of fuel reduction treatments, including salvage logging. This distinction suggests potential trade-offs between (1) reducing fire risk and potential fire intensity in post-disturbance situations and (2) reducing the cumulative forest-floor impact from harvesting combined with wildfire. Recognizing these trade-offs may provide guidance when formulating post-disturbance management prescriptions.

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APPENDIX

Keys for tree crown and forest floor fire-severity index classes (*Ecological Archives* A021-086-A1).