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Title: *Effects of blowdown, salvage logging, and wildfire on regeneration and fuel characteristics in Minnesota's forests*

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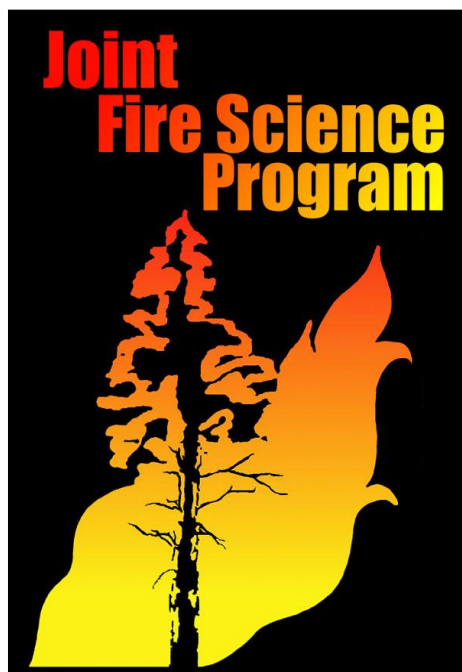
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ABSTRACT

The patchiness resulting from a sequence of recent disturbances – blowdown, salvage logging, and wildfire – provided an excellent opportunity to assess the impacts of these disturbances, singly and in combination, on (1) wildfire severity (2) post-disturbance vegetation responses, (3) ecosystem carbon stocks, and (4) soil mercury (Hg) accumulation or loss in jack pine (*P. banksiana*) forests of northern Minnesota. Considering issue 1, 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. Considering issue 2, our results suggest that disturbance combinations (blowdown and fire with and without salvage logging) resulted in similar woody plant communities, largely dominated by trembling aspen (*Populus tremuloides*). By comparison, areas experiencing solely fire were dominated by jack pine regeneration, and areas experiencing solely blowdown were dominated by regeneration from shade-tolerant conifer species. Considering issue 3, our results suggest that various disturbances cause dramatic shifts in the proportion of carbon in different pools, suggesting that potential increases in multiple disturbance events may represent a challenge for sustaining ecosystem carbon stocks. Considering issue 4, our results suggest that when disturbance combinations are considered in addition to singular disturbances, unexpected consequences in atmospheric Hg emission, soil Hg accumulation, and risk to aquatic biota may result. Taken together, these results lend themselves to improved forest management strategies, particularly regarding post-disturbance harvesting prescriptions.

BACKGROUND AND PURPOSE

Wildfire and other disturbances strongly influence ecosystem structural and successional development, as well as patterns of resource availability, effecting changes at both the site and landscape levels. Traditionally, research has focused on the effects of single disturbances or disturbance types, generating an important body of theory, concepts, and empirical data and producing metrics with which to characterize disturbance regimes (White et al. 1999). Recently, interest has shifted towards the effects of multiple interacting disturbances, such as windthrow, wildfire, and insect outbreaks (e.g., Paine et al. 1998). This work suggests that multiple disturbances may interact synergistically, generating novel ecosystem responses and shifts not readily predicted from knowledge of single disturbances. Given that this is an emerging field of research, much remains unknown regarding the effects of these interactions (Lindenmayer et al. 2010).

One management activity increasingly being examined within the context of interactive disturbance that of salvage logging (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, reducing insect outbreaks, and promoting forest regeneration. However, its ability to achieve these additional objectives remains poorly understood (Lindenmayer et al. 2004, Greene et al. 2006). For instance,

contrary to its intended goals, salvage logging can at times increase subsequent fire severity (Thompson et al. 2007), impede successful natural regeneration (Van Nieuwstadt et al. 2001), and alter the rate and trajectory of forest recovery (Lindenmayer and Ough 2006). Concerns over these unintended consequences may grow in importance given the longer fire seasons and increased disturbance activity projected under a changing climate (Wootton and Flannigan 1993). Further, because salvage logging typically closely follows natural disturbance in time, the cumulative severity of these disturbances (*sensu* Peterson and Leach 2008) may create novel conditions for a given ecosystem (Paine et al. 1998). Yet, to date, few studies have addressed the ecological consequences of such post-disturbance fuel-reduction treatments, particularly in regions outside the Western United States.

Although the impact of singular natural disturbances on forest carbon storage is well recognized, the influence of multiple potentially synergistic disturbances, as well as post-disturbance management prescriptions such as salvage logging, on carbon dynamics remains unclear. This issue is a growing concern because many simulations of future climatic conditions predict greater frequency and intensity of both wildfires and severe windstorms, which may dramatically influence carbon dynamics. By quantifying the impact of both a natural disturbance and salvage logging, this project will make a valuable contribution to our understanding of terrestrial carbon dynamics.

Addressing these issues is particularly timely in northern Minnesota, where a recent sequence of disturbances has created a challenging post-disturbance management situation. On Independence Day, 1999, a severe windstorm damaged nearly 500,000 acres of forest on the Superior National Forest. Between 2000 and 2002, in an effort to reduce fire risk, the Superior NF conducted fuel-reduction treatments, including salvage logging, in the Gunflint Corridor (Figure 1). Then in May, 2007, the Ham Lake fire burned *ca.* 75,500 acres (36,500 in the U.S.) through much of the Gunflint Corridor, including sites that had been salvaged (Figure 1). The various combinations of blowdown, salvage logging, and wildfire represent an opportunity – unique in the Lake States and likely uncommon world-wide – to assess the efficacy of salvage logging in reducing subsequent fire severity. This sequence of events also creates an excellent opportunity to investigate the individual and combined effects of natural disturbances and salvage logging in a region where these issues have received little attention.

Our four objectives have evolved (i.e., improved) from those listed in the original proposal. These objectives, listed below, provide the structure of the *Key Findings*, *Management Implication*, and *Relationship to Other Recent Findings* sections that follow.

Objective #1: Determine if salvage logging reduced subsequent fire severity in conifer-dominated forests of Minnesota.

Objective #2: Characterize vegetation and structural responses following blowdown, salvage logging, and wildfire.

Objective #3: Quantify the effects of blowdown, salvage logging, and wildfire on forest carbon stocks.

Objective #4: Evaluate the effects of blowdown, salvage logging, and wildfire on forest floor and soil mercury pools.

STUDY DESCRIPTION AND LOCATION

This project took place in jack pine (*Pinus banksiana*) forests in and around the Gunflint Corridor of the Superior National Forest, Minnesota (Figure 1). The area has a mean annual precipitation of *ca.* 71 cm; mean temperature of 2° C, with mean July and January temperatures of 17° C and -21° C. Soils of the area are characterized by tills, outwash, and lacustrine deposits of the Rainy glacial lobe, with depth to bedrock varying greatly from 20 cm to over a meter. Historically, forests of this region were dominated by jack pine, eastern white pine (*P. strobus*), red pine (*P. resinosa*), black spruce (*Picea mariana*), white spruce (*P. glauca*), balsam fir (*Abies balsamea*), northern-white cedar (*Thuja occidentalis*), paper birch (*Betula papyrifera*), and trembling aspen (*Populus tremuloides*). The relative composition of these species has shifted over the last 100 years owing to land-use change and fire suppression; however, the jack pine cover type still occupies a large portion of the Superior NF. This forest type is considered fire dependent, with an average fire return interval of 50 to 75 years prior to EuroAmerican settlement (Heinselman 1996).

This sequence of events described above – blowdown, followed by salvage logging, followed in turn by wildfire in 2007 – creates the appropriate backdrop for addressing our objectives. To this end, in 2008 six study sites were established within each of our five treatment types: Blowdown-Salvage-Fire, Blowdown-Fire, Fire, Blowdown, and Control, for a total of 30 sites (Table 1). Depending on site size, 6-10 200-m² circular plots were established at each site at 40-m intervals on a grid pattern originating from a randomly chosen starting point. Within each 200-m² plot, all standing living and dead trees (dbh ≥ 10 cm) were recorded by species and diameter. Saplings (stems of tree species ≥ 2.5 cm and < 10 cm dbh) within each plot were tallied by species. Stems of shrubs and tree seedlings (stems smaller than our sapling class) were tallied by species within one 10-m² circular plot located within the center of each 200-m² plot. Additional tree seedling data were collected from 10-m² plots located equidistant between each large plot for a total of 14-20 seedling plots in each site. In order to characterize the volume of coarse woody debris on each plot, we used the planar intersect method. For this purpose, we established one 32-m transect passing through the center of each 200-m² plot and positioned by random azimuth (Brown 1974). We recorded diameters of all downed woody debris > 7.6 cm in diameter along this transect.

On these same sites, fire severity was assessed in 2008 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, 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 plus humus), 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 uppermost point of charring on tree boles, averaged per plot. All field sampling for fire severity was conducted in May, 2008.

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

Treatment	Number of sites	Number of plots	1999 Blowdown	Salvage Logging	2007 Wildfire
Blowdown-Salvage-Fire	6	49	YES	YES	YES
Blowdown-Fire	6	47	YES	NO	YES
Fire Only	6	51	NO	NO	YES
Blowdown Only	6	48	YES	NO	NO
Control	6	45	NO	NO	NO

KEY FINDINGS

Objective #1: Salvage logging and fire severity.

Summary of Findings: 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.

Objective #2: Vegetation and structural responses.

Summary of Findings: We examined the structural and woody plant community responses of sub-boreal jack pine systems to a rapid sequence of multiple disturbances, including windthrow, salvage logging, and wildfire, in northeastern Minnesota, USA. Comparisons between areas experiencing windthrow followed by wildfire with areas in which salvage logging was juxtaposed between these two events indicated that salvage logging decreased the abundance of structural legacies, such as downed woody debris and snags. Both of these disturbance combinations (blowdown and fire with and without salvage logging), resulted in similar woody plant communities, largely dominated by trembling aspen. By comparison, areas experiencing solely fire were dominated by jack pine regeneration, and blowdown areas were largely characterized by regeneration from shade tolerant conifer species. Our results suggest that salvage logging impacts on woody plant community are diminished when followed by a second high severity disturbance; however, impacts on structural legacies remain.

Objective #3: Carbon consequences.

Summary of Findings: We quantified how forest carbon stocks responded to stand-replacing blowdown and wildfire, both individually and in combination with and without post-disturbance salvage operations, in a sub-boreal jack pine ecosystem. Individually, blowdown or fire caused similar decreases in live carbon and total ecosystem carbon. However, whereas blowdown increased carbon in down woody material and forest floor, fire increased carbon in standing snags, a difference that may have consequences for long-term carbon cycling patterns. Fire after the blowdown caused substantial additional reduction in ecosystem carbon stocks, suggesting that potential increases in multiple disturbance events may represent a challenge for sustaining ecosystem carbon stocks. Salvage logging, as examined here, decreased carbon stored in snags and down woody material but had no significant effect on total ecosystem carbon stocks.

Objective #4: Mercury pools.

Summary of Findings: We assessed the singular and combined effects of multiple disturbances on forest floor and soil total Hg concentrations and pools. Although no treatment effects were found for mineral soils, we did see significant effects for both concentrations and pools in the forest floor. Blowdown increased the mean Hg pool in the forest floor by $0.76 \text{ mg Hg m}^{-2}$ (223%), while salvage logging following blowdown created conditions that enhanced Hg emission from the forest floor during subsequent fire. This sequence of combined events resulted in a mean loss of $0.52 \text{ mg Hg m}^{-2}$ (84% of pool). Fire alone or blowdown followed by fire did not significantly affect the total Hg concentrations or pools in the forest floor. Overall, unexpected consequences for atmospheric Hg emission, soil Hg accumulation, and risk to aquatic biota may result when combined impacts are considered in addition to singular forest and soil disturbances.

MANAGEMENT IMPLICATIONS

Objective #1: Salvage logging and fire severity.

Implications: Our 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. 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. Finally, our results clearly highlight the importance of distinguishing between fire intensity and severity when gauging the efficacy of fuel reduction treatments, including salvage logging. This distinction suggests potential tradeoffs 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 tradeoffs may provide guidance when formulating post-disturbance management prescriptions.

Objective #2: Vegetation and structural responses.

Implications: Ours is one of the first studies to evaluate how a sequence of disturbances occurring in rapid succession (i.e., blowdown, salvage logging, wildfire) affects ecosystem structure and composition. The general similarities we documented in successional trajectories between sites experiencing blowdown followed by wildfire and those in which salvage logging occurred between these two disturbances suggest that salvage logging impacts on regeneration are diminished when followed by a second major disturbance. While post-blowdown salvage logging clearly reduces fuel loads (a consideration in fire-prone areas), it also has long lasting impacts on the structure of post-fire communities, including a reduction in snags and downed woody debris. Given the importance of these structural legacies in aiding ecosystem recovery following disturbance (Franklin et al. 2000), the retention of these features during post-disturbance management should receive greater consideration. Provisions for the retention of these and other biological legacies as part of salvage logging operations will ensure that these operations meet objectives related to long-term ecosystem recovery, as well as short-term recovery of economic value. Planning and guideline development pertaining to the retention of these legacies should strive to create a mosaic of salvaged and unsalvaged areas, thereby reducing fire spread through the landscape while also emulating the historic variation in disturbance severity experienced by these systems.

Objective #3: Carbon consequences.

Implications: Our results have two primary implications for management. First, the magnitude of additional carbon losses owing to fire following blowdown suggests that increasing disturbance frequencies may represent a substantial challenge for land management efforts to sustain and enhance ecosystem carbon stocks (Birdsey et al. 2006). Second, these results indicate that salvage operations, which may not necessarily

decrease fire risk or severity (this study), could further reduce dead-wood carbon pools relative to natural disturbance. It is important to note that these results are based on observations of carbon stocks only a year after the final disturbance. The fact that disturbances have lasting consequences points to the importance of following the long-term patterns in recovery of ecosystem structure, composition and carbon dynamics.

Objective #4: Mercury pools.

Implications: Our results demonstrate the importance of considering both singular and multiple forest disturbances on Hg emission from, or accumulation in, the forest floor. The singular effect of blowdown increased forest floor THg (total Hg) pools and may lead to Hg bioaccumulation in aquatic biota of affected watersheds, as this pool appears to contribute to THg (and possibly methylmercury) in runoff to surface waters (Kolka et al. 2001). Only in watersheds where multiple disturbances occurred prior to fire did we observe substantial Hg losses. Given the close relationships observed in the region between watershed O-horizon Hg concentrations and Hg accumulation in fish (Gabriel et al. 2009), substantial losses of Hg to the atmosphere may be locally beneficial to aquatic biota because less Hg would be available to contribute to runoff into lakes and possibly methylation. Because the combination of blowdown, salvage logging, and wildfire dramatically decreased both THg concentrations and pools, it may take decades, perhaps centuries, for Hg to accumulate to pre-disturbance levels (Woodruff and Cannon 2010), which could decrease Hg levels in nearby aquatic biota over this time period. A tradeoff exists however, as the fate of the Hg released to the atmosphere is difficult to track; it is eventually deposited back to the surface, possibly leading to increased bioaccumulation elsewhere.

RELATIONSHIP TO OTHER RECENT FINDINGS

Objective #1: Salvage logging and fire severity.

Relationship to Recent Findings: 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 results lend support for our hypothesis that salvage logging would reduce tree-crown severity in a subsequent fire; however, the forest-floor severity was increased by salvage logging. The tree-crown severity 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.

Objective #2: Vegetation and structural responses.

Relationship to Recent Findings: This study represents, to our knowledge, the first examination of the impacts of salvage logging on forest community composition and successional trajectories when juxtaposed between two natural disturbances (windthrow and wildfire). We found that salvage logging tended to homogenize the post-fire woody plant communities, a finding consistent with that of Purdon et al. (2004) who documented a general homogenization of understory vegetation within burned areas experiencing salvage logging relative to areas solely experiencing high-severity fires. Consistent with the findings of Peterson and Leach (2008), we did not observe lower levels of woody species richness, diversity, or cover in areas experiencing salvage logging relative to other disturbance types. Post-disturbance regeneration within burned treatments was consistent with the patterns observed following high-severity crown fires in jack pine systems in other portions of the upper Great Lakes region (Greene et al. 2004, Jayen et al. 2006). In contrast, the treatments experiencing compound disturbances (i.e., Blowdown-Salvage-Fire and Blowdown-Fire) were largely dominated by trembling aspen, a finding consistent with Frelich's (2002) predictions regarding the impacts of extremely high cumulative disturbance severities on the successional trajectory in this system. The dominance of shade-tolerant tree seedlings and saplings in stands solely experiencing blowdown is consistent with the findings of other work examining regeneration patterns after the 1999 blowdown in northern Minnesota (Rich et al. 2007).

Objective #3: Carbon consequences.

Relationship to Recent Findings: Very little has been published on the carbon consequences of salvage logging or disturbance interactions. Our finding of lower carbon stocks in younger, post-disturbance, post-salvage forests is consistent with those of Johnson et al. (2005), and lower total ecosystem carbon, when compared to the undisturbed control, follows findings and predictions from post-disturbance chronosequences such as that of Bradford et al. (2008).

Objective #4: Mercury pools.

Relationship to Recent Findings: Very little has been published on the mercury consequences of salvage logging or disturbance interactions. Our findings differed between mineral soil and forest floor components. For example, little post-disturbance Hg volatilization occurred from mineral soil, presumably owing to the insulation from abundant litter, which has been reported in other post-fire situations (DiCosty et al. 2006, Biswas et al. 2008). In contrast, the forest floor experienced the greatest Hg losses in the cumulative Blowdown-Salvage Logging-Fire treatment, which could perhaps be expected from the greater solar radiation, and hence volatilization (Gustin et al. 2002) in the salvaged areas, as well as alterations to the forest floor by harvesting equipment that may have compacted the duff, leading to increased smoldering combustion (DeBano et al. 1998) and hence greater Hg emission to the atmosphere.

FUTURE WORK NEEDED

Long-term Monitoring: Given the nature of the funding, our results depict conditions one year post-fire. Ideally, long-term monitoring of these sites would be undertaken, as disturbance-related patterns and trajectories may emerge that could not have been predicted from our short-term assessment. One question critical to the concept of multiple disturbances occurring in rapid sequence (Paine et al. 1998) is if the recovery time is more protracted than would be expected from singular disturbances. This question could only be answered with long-term data.

Fire Severity Assessments: Robust comparisons between detailed ground-based fire-severity assessments (as we have employed in this study) and those conducted by remote sensing would shed light on the utility of both approaches, including areas needing improvement. This is an important consideration because ground-based measures may not correlate well with remotely-sensed measures (Halofsky and Hibbs 2009, De Santis and Chuvieco 2009). Finally, researchers currently use a wide range of ground-based fire-severity assessments, often developed for a particular study. Work is clearly needed to standardize these assessments for cross-study and cross-site comparisons. This standardization would nicely complement recent attempts to standardize forest-science terminology (e.g., Keely 2009).

Tradeoffs between Fuel Reduction and Legacy Retention: The reduction in fuel loads resulting from post-disturbance salvage logging may have negative consequences for organisms that benefit from down woody debris and snags (i.e., coarse fuels). Thus the retention of deadwood during post-disturbance management should receive greater consideration, as their presence can ameliorate salvage logging impacts on vegetation communities (e.g., Macdonald 2007). Of additional importance within jack pine forests is the retention of post-disturbance cone-bearing slash (i.e., fine fuels) as seed sources for establishment of this species (Greene et al. 2006). These considerations suggest that meaningful tradeoffs exist between fuel-reduction treatments and deadwood legacy retention, a topic that clearly requires more research attention.

Estimating Fuel Loads: Our preliminary work, unrelated to this Joint Fire Science project, suggests that the standard method of assessing fuel loads, namely the line-intercept method (Brown 1974), may underestimate fuel abundance. The theory underlying the line-intercept method is quite well developed, and has been for some time (Warren and Olsen 1964, van Wagner 1968). The method has been shown to produce unbiased estimates, providing that several assumptions are met. These assumptions include horizontal position of pieces, random orientation and distribution of pieces, and cylindrical or conically-tapered pieces (Warren and Olsen 1964, van Wagner 1968). To what extent typical field inventories meet these assumptions, and the possible biases incurred by failure to meet these assumptions, remains untested. A rigorous evaluation of this method is both timely and warranted.

DELIVERABLES CROSS-WALK

This Joint Fire Science project has produced four presentations (to date) and four peer-reviewed papers (currently 1 published, 1 in press, 2 in review). The fourth publication (an assessment of wildfire and other disturbances on soil mercury, see below) resulted from an objective we added to the original proposal.

Table 2. Deliverables cross-walk.

Deliverable	Description (from Proposal)	Status (will be updated)
Scientific Presentations	1 Presentation each on fuels/fire severity, forest regeneration, and carbon storage	We delivered 4 presentations (to date), although topics differed slightly than those proposed (see below)
On-site workshop	Workshop at research site to illustrate and demonstrate results for managers	We were not able to accomplish this
Technical report	The long-term effect of fuels reduction treatments on fuel loading and regeneration.	D'Amato et al. manuscript in press as a peer-reviewed paper (see below)
Refereed publication	Impact of post-disturbance salvage logging on fire severity, fuel loads, and regeneration	Fraver et al. manuscript published as a peer-reviewed paper, not a technical report (see below)
Refereed publication	The impact of catastrophic disturbances and subsequent treatments on carbon storage	Bradford et al. manuscript in review as a peer-reviewed paper (see below)

Deliverable #1 (Presentations):

Dunn, L. and D. Shinneman. *Post-blowdown salvage logging impacts on fuel loads and fire severity: preliminary results from the Boundary Waters Blowdown and Ham Lake Fire*. Oral Presentation. The Future of Fire and Wind in Northern Minnesota Forests: Lessons Learned from the 1999 Blowdown (Workshop). 18 February, 2009. Cloquet Forestry Center, Cloquet, Minnesota.

Fraver, S., J. Bradford, B. Palik, D. Kastendick, T. Jain, J. Stanovick, T. D'Amato, L. Patty, D. Shinneman. *Efficacy of salvage logging in reducing subsequent fire severity*. Oral Presentation. Superior National Forest Research Roundup. 22 January, 2010. Superior National Forest, Supervisor's Office, Duluth, Minnesota.

Mitchell, C., R. Kolka, and S. Fraver. *Influence of blowdown, fire and salvage logging on forest floor and soil mercury pools*. Oral Presentation. International Conference on Mercury as a Global Pollutant. 24 – 29 July, 2011. Halifax, Nova Scotia.

Fraver, S. *Applied Forest Ecology: Learning from the Past, Looking to the Future*. Oral Presentation (included results of this JFSP project). 15 June, 2010. University of New Hampshire, Durham, New Hampshire.

Deliverables #3, #4, #5 (Publications):

D'Amato, D., S. Fraver, J. B. Bradford, and B. Palik. *In Press*. Vegetation response following blowdown, salvage logging, and fire in northern Minnesota. *Forest Ecology and Management*.

Fraver, S., T. Jain, J.B. Bradford, A.W. D'Amato, D. Kastendick, B.J. Palik, and D. Shinneman. 2011. The efficacy of salvage logging in reducing subsequent fire severity in conifer-dominated forests of Minnesota, USA. *Ecological Applications* 21(6): 1895-1901.

Bradford, J.B., A. Milo, S. Fraver, A.W. D'Amato, and B.J. Palik. Effects of multiple interacting disturbances and salvage logging on forest carbon stocks in northern Minnesota. *In review*.

Mitchell, C.P.J., R.K. Kolka, and S. Fraver. The singular and combined effects of blowdown, salvage logging, and wildfire on forest floor and soil mercury pools. *In review*.

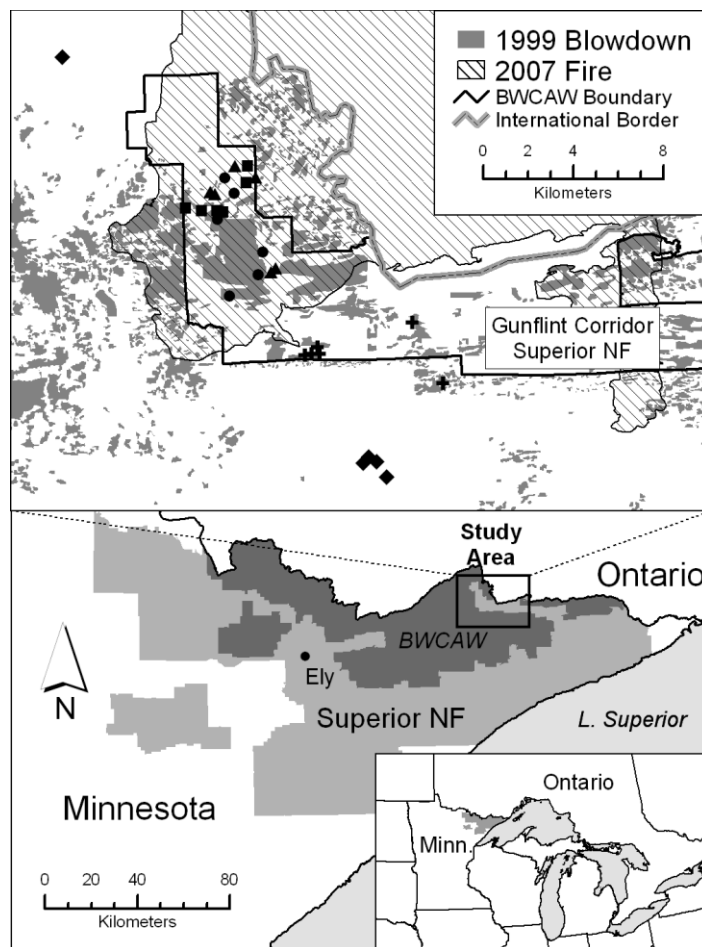


Figure 1. Location of study sites and disturbance areas in jack pine forests of northeastern Minnesota, USA. One site to the east of the study area shown above was excluded for convenience of presentation. Site codes: ■ = Blowdown-Salvage-Fire, ● = Blowdown-Fire, ▲ = Fire only, + = Blowdown only, ◆ = Control.

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