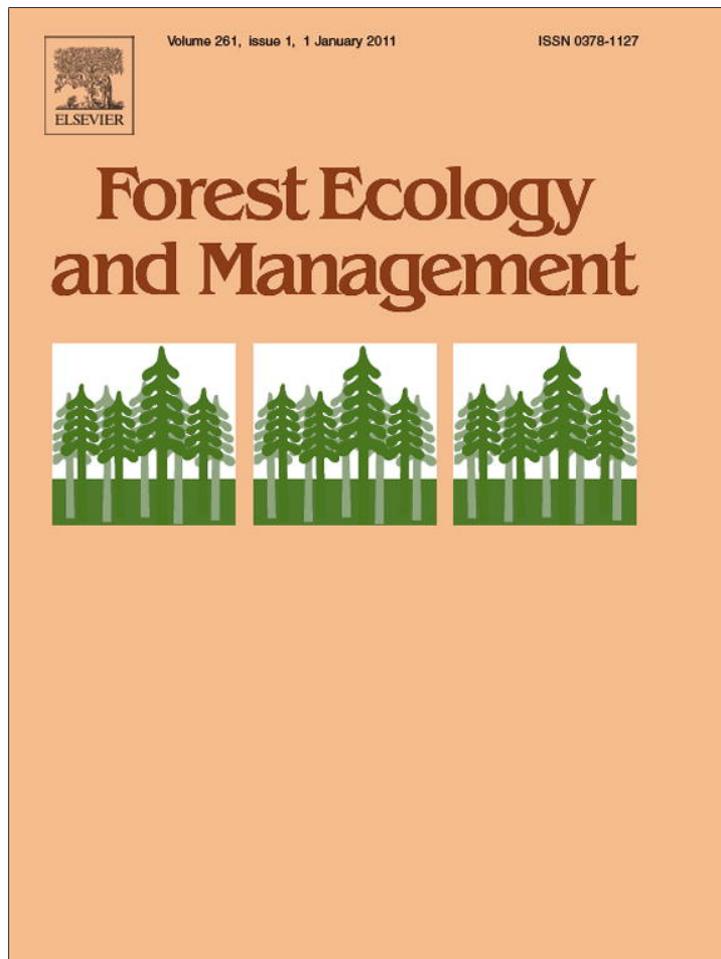


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## Effects of multiple interacting disturbances and salvage logging on forest carbon stocks

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### ABSTRACT

Climate change is anticipated to increase the frequency of disturbances, potentially impacting carbon stocks in terrestrial ecosystems. However, little is known about the implications of either multiple disturbances or post-disturbance forest management activities on ecosystem carbon stocks. This study 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.

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### 1. Introduction

As the link between elevated atmospheric carbon dioxide concentrations and changing climatic conditions becomes increasingly clear (IPCC, 2007), forest management is shifting to include the broad goal of maintaining and maximizing carbon stocks (Malmsheimer et al., 2008). Globally, forests contain over 80% of above-ground terrestrial carbon; relatively minor alterations to carbon stocks or cycling in forest ecosystems may have substantial impacts on atmospheric carbon dioxide (Pacala et al., 2001; Bonan, 2008). However, climate change is anticipated to increase the severity and frequency of natural disturbances (Schelhaas et al., 2003), potentially decreasing the ability of forests to sustain carbon stocks (Galik and Jackson, 2009).

Meso- to large-scale disturbances are known to influence carbon cycling and stocks in terrestrial ecosystems (Dale et al., 2001). In forests, many stand-replacing disturbance agents, including windthrow, wildfire, and insect outbreaks, typically result in decreased ecosystem carbon stocks for several decades post-disturbance (Pregitzer and Euskirchen, 2004) and may become more

prevalent as climate conditions continue to change. Moderate to severe intensity wind gusts are expected to increase (Meehl et al., 2000) and can cause widespread damage and tree mortality, impacting carbon balance at landscape to regional scales (Chambers et al., 2007; Lindroth et al., 2009). Similarly, the severity and frequency of insect outbreaks are linked in part to temperature and moisture, and mortality from such outbreaks decreases forest carbon stocks over very large areas (Kurz et al., 2008). Wildfire frequency and severity has been linked to increasing temperatures and changes in rainfall patterns (Westerling et al., 2006) and carbon emissions from wildfires can be significant (Campbell et al., 2007; Wiedinmyer and Neff, 2007).

As disturbance frequencies increase, the possibility of multiple disturbances occurring in rapid succession, relative to a system's recovery rate, becomes more likely (Paine et al., 1998; Burkett et al., 2005). Although the impact of individual disturbances on forest carbon storage is recognized and relatively well characterized, the consequences of multiple, interacting disturbances are essentially unknown (Dale et al., 2001). In addition, forest managers are responding to more frequent and widespread disturbances by applying salvage-logging treatments to mitigate wildfire risk and/or recover economic value of trees within impacted areas (Lindenmayer et al., 2008), yet the influence of such post-disturbance

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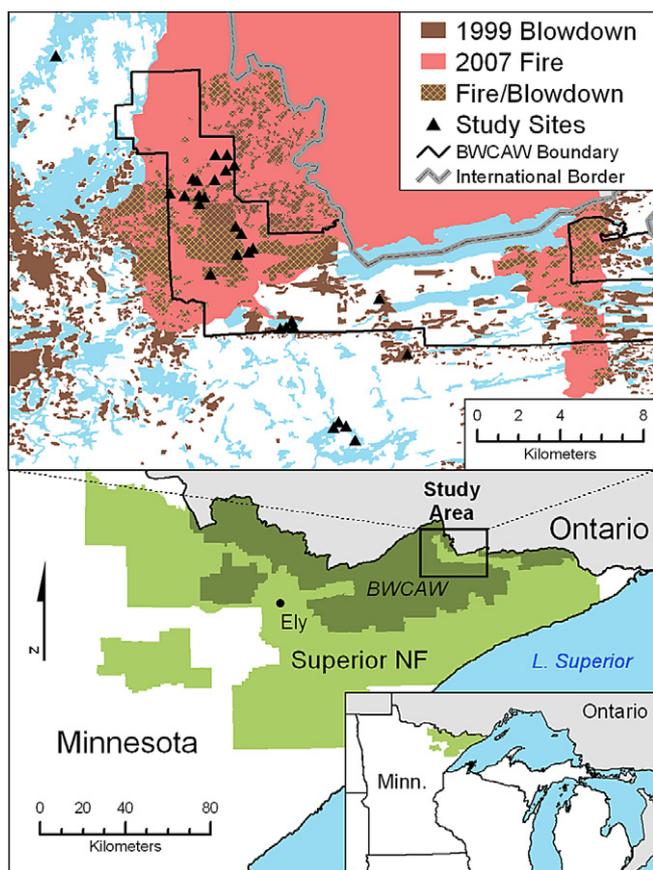


Fig. 1. Location of 1999 blowdown, 2007 wildfire and study sites within the Superior National Forest of Northern Minnesota.

management prescriptions on carbon dynamics remains relatively unexamined (although see Serrano-Ortiz et al., 2011).

This study examined the consequences of multiple interacting disturbances, including post-disturbance salvage logging, on forest ecosystem carbon storage in Northern Minnesota. In 1999, a derecho (a widespread, straight-line windstorm) event exceeded 145 km/hr and disturbed a large area of sub-boreal forest in Northern Minnesota and Southern Ontario (Fig. 1). Over the next 3 years, the US Forest Service implemented salvage logging operations in part of the wind-disturbed area to reduce fuel loads (USDA Forest Service, 2000). Despite these efforts, a large wildfire burned through much of the previous blowdown and salvage areas in 2007. We capitalized on this sequence of disturbances – blowdown, salvage logging, and wildfire – and characterized their effects, singly and in combination, on ecosystem carbon dynamics. Our objective was to quantify changes in carbon stocks in all ecosystem carbon pools that occurred as a consequence of these individual and combined disturbances.

## 2. Materials and methods

### 2.1. Study site

The study was conducted in Northeastern Minnesota, USA, along the Southern edge of the North American boreal forest ecotone, and within the Superior National Forest (Fig. 1). Glacial activity has shaped the landscape, which consists of rolling topography and mostly shallow soils over a substrate of Precambrian bedrock (Heinselman, 1973). The area has a cold continental climate; mean annual temperature, and precipitation are 2 °C and 68 cm, respectively.

On 4 July 1999, a massive derecho produced straight-line winds affecting over 200,000 ha of the Superior National Forest (Woodall and Nagel, 2007). Following the storm, the US Forest Service began a sequence of salvage logging operations to reduce fuel loads (Gilmore et al., 2003). For the areas examined here, salvage logging occurred between the fall of 1999 and fall of 2002. In the spring of 2007, part of the region was burned by the Ham Lake wildfire (Fig. 1). Patchy, overlapping disturbance patterns resulted in five “treatments:” undisturbed control, blowdown only, fire only, blowdown followed by fire (BF), and blowdown followed by salvage logging followed by fire (BSF). Unburned salvaged areas did not exist. We focused on mature jack pine (*Pinus banksiana*) communities.

### 2.2. Plot establishment

In 2008, we established six study sites in each of these five disturbance combinations, for a total of 30 sites. We chose eight of these sites because of existing data from an earlier study (Gilmore et al., 2003) that examined fuel loads following the 1999 blowdown. Using US Forest Service stand-type maps, we randomly selected the remaining 22 sites from a complete set of potential sites for each disturbance combination. Although we lacked pre-disturbance data for most of our sites, comparisons of C treatment stand structures and reconstructed structures for the other treatments (based on deadwood pools) with the plots with pre-existing data (Gilmore et al., 2003) confirmed that all sites were comparable regarding pre-disturbance stand structure and successional stage. Randomly selected sites were ground-truthed for adherence to the expected forest type and disturbance combination. At each site, 6–10 circular plots (200-m<sup>2</sup>) were established along 40 × 40 m grid that originating from a randomly chosen starting point, for a total of 239 plots. These sites and plots were established as part of a broader set of companion studies addressing fire severity and vegetation responses.

### 2.3. Field measurements

Within each circular plot, standing live, and dead trees (diameter at breast height, dbh, ≥ 10 cm) and saplings (stems of tree species ≥ 2.5 cm and < 10 cm dbh) were recorded by species and diameter. Stems of shrubs and tree seedlings (stems smaller than our sapling class) were tallied by species within a 10-m<sup>2</sup> circular plot centered in each 200-m<sup>2</sup> plot. Additional seedling data were collected in 10-m<sup>2</sup> plots located equidistant between each 200-m<sup>2</sup> plot, resulting in 14–20 seedling plots at each site. Downed woody debris (DWD) on each plot was inventoried following Van Wagner (1968). We thus recorded diameters of all DWD ≥ 7.6 cm in diameter along a 32-m transect passing through the center of each 200-m<sup>2</sup> plot and aligned by random azimuth. At a set location within each 200-m<sup>2</sup> plot, we separately collected samples of herbaceous vascular plant material, forest floor material, and soils. Plant material was clipped and collected within a 0.25 m<sup>2</sup> frame; forest floor material was collected within a 25-cm diameter collar; soil was collected with a 4-cm diameter core to a depth of 10 cm.

### 2.4. Calculation of carbon pools

The biomass of living and intact standing dead trees was calculated for all woody stems > 2.5 cm dbh using species-specific allometric equations that were regionally derived where possible (Perala and Alban, 1993; Jenkins et al., 2003). The biomass of broken standing dead trees was estimated using taper functions (Woodall et al., 2008) to determine large and small end diameters and then applying the conic-paraboloid formula (Fraver et al., 2007) to determine the volume of the intact portion of the tree.

Volume was converted to biomass using species-specific density values for decay class I taken from Harmon et al. (2008). For standing dead trees that could not be identified to species, we used the average of decay class II densities from all species present. Shrub and tree seedling biomass was calculated using species-specific allometric equations (Grigal and Ohmann, 1977; Roussopoulos and Loomis, 1979; Perala and Alban, 1993). Biomass calculations for these components included stems, roots, branches, as well as foliage if alive.

Dead woody debris biomass was determined using Van Wagner's formula (1968) applied to the planar intercept data, adjusting for species – and decay class-specific densities (Harmon et al., 2008). The volume of coarse woody debris in decay class IV or V was adjusted for collapse using collapse ratios of 0.82 and 0.42, respectively (the ratio of vertical and horizontal diameters from S. Fraver: unpublished data from this region). Carbon content was derived from total biomass using species-specific values (Lam-lom and Savidge, 2003), or assumed to be 50% of biomass for shrub species and unidentified DWD (Heath et al., 2003).

### 2.5. Statistical analysis

Differences in carbon pool sizes among treatments (i.e. disturbance combinations) were tested using separate mixed-model analyses of variance (ANOVA) in which disturbance combination was treated as a fixed effect and site as a random effect. Analyses of variance was calculated for carbon stored in live trees, understory (herbaceous plants, shrubs, and seedlings), live biomass (sum of live trees and understory), DWD, snags, dead woody material (snags plus DWD), forest floor, soil, and total ecosystem carbon (sum of live biomass, deadwood, forest floor, and soil). In cases in which significant disturbance effects were detected, post hoc Tukey's honest significant difference tests were used for pairwise comparisons between disturbance types. Prior to ANOVA, data distributions were checked for normality and transformed using natural logarithmic or square-root transformations as necessary. Analyses of variance was conducted using SAS version 9.2 (SAS Institute, Inc.). An alpha-value of 0.05 or less was considered significant.

### 3. Results

Carbon in live biomass was stored primarily in live trees. Total live carbon and carbon in live trees were highest in the control (Fig. 2, mean = 104 MgC ha<sup>-1</sup>) and lower in all other treatments (from 1 MgC ha<sup>-1</sup> in the blowdown-salvaged-fire (BSF) treatment to 21 MgC ha<sup>-1</sup> in the blowdown treatment). Carbon in understory biomass was higher in the BSF treatment (mean = 1.3 MgC ha<sup>-1</sup>) than control, blowdown, or fire treatments (0.2–0.6 MgC ha<sup>-1</sup>). Carbon in snags was much higher in the fire treatment (mean = 53 MgC ha<sup>-1</sup>) than other treatments, and the blowdown-fire (BF) treatment (mean = 19 MgC ha<sup>-1</sup>) was higher than the BSF treatment (mean = 1.7 MgC ha<sup>-1</sup>). By contrast, carbon in DWD (down wood) was much higher in the blowdown stands (mean = 35 MgC ha<sup>-1</sup>) than all others, intermediate in the BF treatment (mean = 21 MgC ha<sup>-1</sup>) and lowest in all other treatments (9–10 MgC ha<sup>-1</sup>). Carbon in all dead woody material (snags and DWD) was highest in the fire treatment (mean = 62 MgC ha<sup>-1</sup>) and lowest in the BSF treatment (mean = 11 MgC ha<sup>-1</sup>), with other treatments ranging from 22 to 43 MgC ha<sup>-1</sup>. Carbon stored in the forest floor was highest in the blowdown treatment (mean = 35 MgC ha<sup>-1</sup>) and lowest in the BSF treatment (mean = 9 MgC ha<sup>-1</sup>). Soil carbon means ranged between 13 and 32 MgC ha<sup>-1</sup> and were not significantly different among treatments. Total ecosystem carbon was highest in the control treatment (mean = 177 MgC ha<sup>-1</sup>), intermediate in the blowdown and fire treatments (means = 122

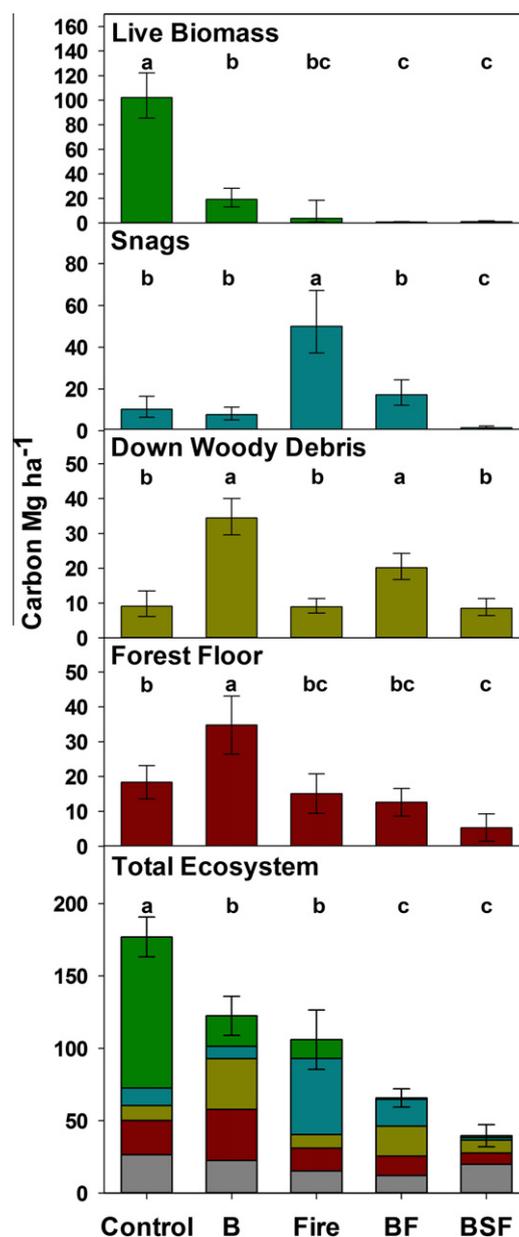
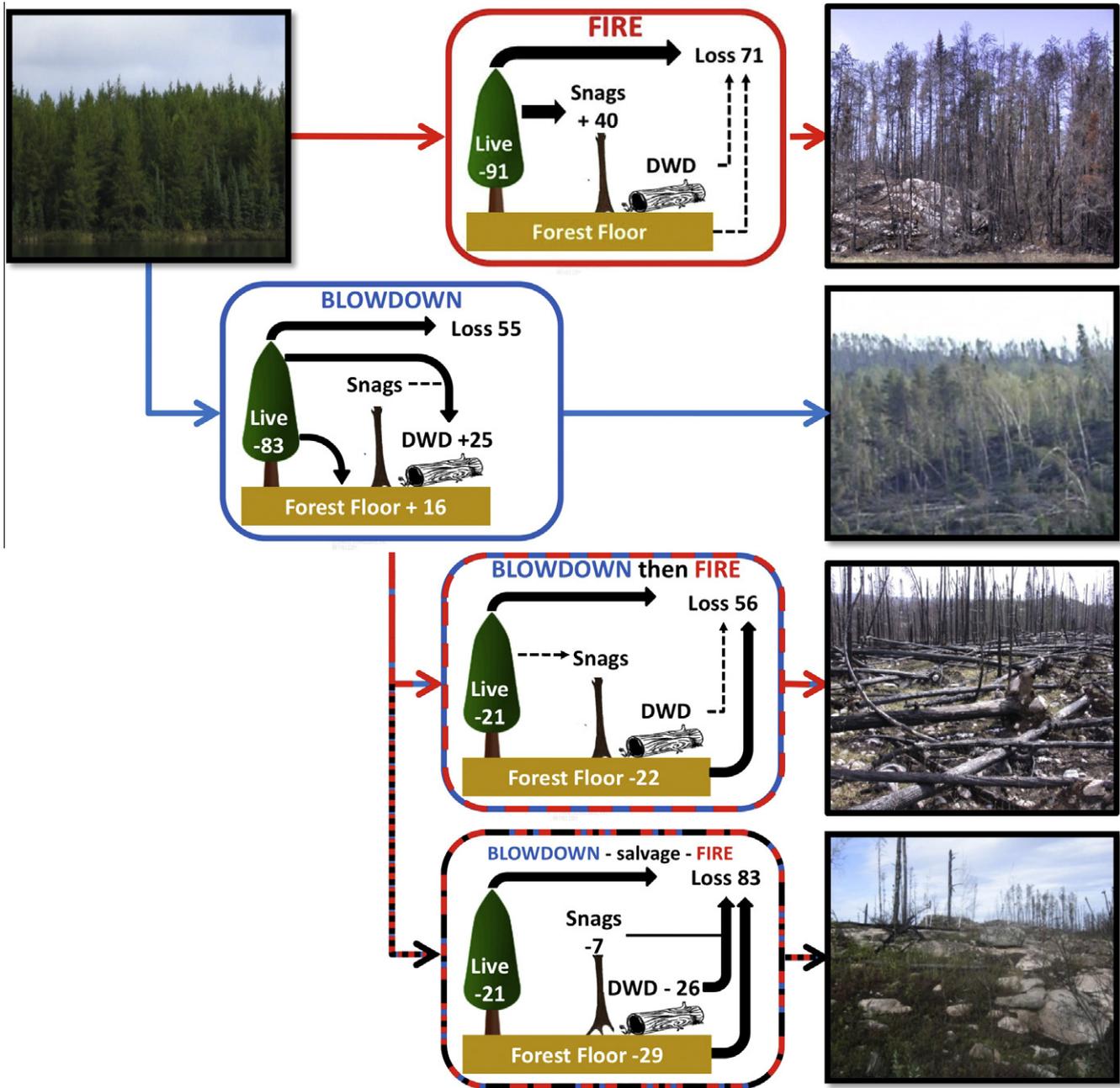


Fig. 2. Carbon stocks for individual pools and total ecosystem carbon for forest stands experiencing no recent disturbance (control), blowdown (B), wildfire (Fire), and both wind and wildfire with (BSF) and without salvage logging (BF). Error bars are 95% confidence intervals around treatment means, back-transformed as necessary. Lower case letters indicate significant differences among treatments. Gray bars (bottom of the stacked bars reflecting total ecosystem carbon) are soil carbon (not statistically different among treatments).

and 106 MgC ha<sup>-1</sup>, respectively) and lowest in the BF and BSF treatments (means = 66 and 40 MgC ha<sup>-1</sup>, respectively).

Differences in these carbon pools (using the controls as a baseline for comparison, Fig. 3) indicate that individual natural disturbances, either blowdown or fire, resulted in roughly similar decreases in live carbon of 83 and 91 MgC ha<sup>-1</sup>, respectively, and loss in total ecosystem carbon of 55 and 71 MgC ha<sup>-1</sup>, respectively. Blowdown increased DWD carbon by 25 MgC ha<sup>-1</sup> and forest floor carbon by 16 MgC ha<sup>-1</sup> and had no significant effect on snag carbon. Fire, by contrast, increased snag carbon by 40 MgC ha<sup>-1</sup>. Compared to blowdown alone, fire following blowdown decreased both DWD and forest floor carbon by another 14 and 22 MgC ha<sup>-1</sup>, respectively, and resulted in additional total ecosystem carbon losses of 56 MgC ha<sup>-1</sup>. Likewise, salvage logging and fire after



**Fig. 3.** Consequences of windthrow (1999) and subsequent salvage logging (2000–2002) and wildfire (2007) on ecosystem carbon stocks, measured in 2008. Carbon stocks are partitioned into live biomass, snags, down woody debris (DWD), forest floor (FF). Soil (measured to 10 cm depth and not significantly different among treatments) is not shown. Statistically significant stock differences and total carbon loss are shown in MgC ha<sup>-1</sup>. Arrow widths are roughly proportional to fluxes inferred from pool changes; dashed arrows suggest potential fluxes from stocks where changes were not statistically significant.

blowdown decreased carbon in both DWD and forest floor by another 26 and 29 MgC ha<sup>-1</sup>, respectively, and caused additional total ecosystem carbon loss of 83 MgC ha<sup>-1</sup> compared to blowdown alone.

#### 4. Discussion

Disturbances exert pervasive influence over carbon cycling in forest ecosystems (Dale et al., 2001; Fahey et al., 2010) and are increasingly recognized as an important driver of forest carbon over very large areas (Goward et al., 2008; Kurz et al., 2008). The impacts of stand-replacing disturbances on carbon stocks are demonstrated by the well-recognized positive relationship between

stand age and carbon stocks (Pregitzer and Euskirchen, 2004; Kashian et al., 2006). Carbon stocks are lower in younger, post-disturbance forests and gradually increase with both tree age and time since disturbance (Bradford et al., 2008). Consistent with these general patterns, we found that all combinations of disturbances resulted in lower total ecosystem carbon than the undisturbed control. In addition, our results indicate that individual disturbances, either wind or fire, resulted in remarkably similar shifts of carbon from live biomass to detrital pools (41 and 40 MgC ha<sup>-1</sup> respectively) as well as similar losses of total ecosystem carbon (55 and 71 MgC ha<sup>-1</sup> respectively). Since both the blowdown and fire disturbances we examined were largely stand replacing in nature (D'Amato et al., 2011), the similarity in total

ecosystem carbon lost likely reflects the amount of carbon immediately lost from live trees. The slightly higher inferred loss of total ecosystem carbon in fire compared to blowdown may be a result of direct carbon emissions during combustion (Campbell et al., 2007).

Although both blowdown and fire resulted in  $\sim 40 \text{ MgC ha}^{-1}$  shifting to detrital pools, the destinations for this carbon are different in ways that may influence long-term carbon cycling. While blowdown shifted live tree carbon into downed woody debris and forest floor pools, fire shifted this carbon into snags, which are drier, more isolated from the soil, and generally have slower decomposition rates than downed wood or forest floor (Mackensen et al., 2003). Slower decomposition in the snags may be further magnified by their high charcoal content following fires, which has extremely slow decomposition rates and can be eventually incorporated into soil carbon (DeLuca and Aplet, 2008). Although the long-term consequences of these differences are beyond the scope of this project, the dramatic differences in detrital carbon pool sizes and the ubiquitous presence of charcoal (see pictures in Fig. 3) suggests the possibility for prolonged enhancement of carbon stocks following fires and warrant further investigation.

Because changing climate and land use practices may increase disturbance frequency, the potential for interactions and non-additive impacts as a result of multiple disturbances has been identified as a major unexplored question (Paine et al., 1998; Dale et al., 2001; Turner, 2010). Our results suggest that secondary major disturbances can cause substantial additional decreases in ecosystem carbon, although the magnitude may vary depending on the time between successive disturbances and disturbance types involved. Fire after blowdown resulted in an additional loss of  $\sim 56 \text{ MgC ha}^{-1}$ , essentially identical to the initial loss of total ecosystem carbon observed from wind alone. These additional losses illustrate the effects that interacting disturbances can have on ecosystem carbon stocks. The original blowdown disturbance substantially increased carbon stored in DWD and forest floor, providing larger surface fuel loads that increased burn severity and subsequent carbon loss (Fraver et al., 2011). Although both forest floor and DWD carbon pools were elevated after the blowdown, the subsequent fire appeared to release all of the carbon added to litter in the forest floor and more than half of the carbon added to DWD.

Also relatively unexplored are the impacts of forest management activities, such as salvage logging, on carbon cycling (Lindenmayer et al., 2008). Our results suggest that salvage logging modestly enhanced carbon losses compared to blowdown and fire alone. Post-blowdown salvage logging prior to fire decreased carbon in DWD to control levels, in essence removing all of the carbon added to DWD in the blowdown. Salvage logging also resulted in less carbon stored in snags than that of un-salvaged areas, and slightly, although non-significantly, less carbon in forest floor. Despite these impacts on individual carbon pools, total ecosystem carbon did not differ statistically between salvaged areas and areas that experienced blowdown and fire only. This may be in part a consequence of the high spatial variability in forest carbon pools following multiple disturbances, and/or it may indicate that the combination of blowdown and fire released most of the carbon in vulnerable pools and that the bulk of remaining carbon is stored in mineral soil horizons (e.g. Fig. 2) that are generally not impacted by most disturbances or management activities (Nave et al., 2010). Nonetheless, the lack of charred snags within salvaged logged areas may result in greater long-term carbon losses in these systems relative to areas experiencing the combination of blowdown and fire.

## 5. Conclusions

These results have two primary implications for forest management. First, the magnitude of additional carbon losses due 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; Galik and Jackson, 2009). Second, these results indicate that salvage operations, which may not necessarily decrease fire risk or severity (Fraver et al., 2011), could further reduce dead woody carbon pools relative to natural disturbance or un treated areas (Serrano-Ortiz et al., 2011). However, the reduction in carbon stocks may be only a short-term consequence when later followed by fire. It is important to note that these results are based on observations of carbon stocks only a year after the final disturbance. In addition, this study did not account for the fate or longevity of carbon stored in the salvaged logs, which can exert substantial influences over long-term total-system carbon balance (Marland and Marland, 2003). Because disturbances can have lasting consequences (Foster et al., 1998), additional studies are needed to characterize long-term patterns in recovery of ecosystem structure, composition, and carbon dynamics.

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