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Woody plant regeneration after blowdown, salvage logging, and prescribed fire in a northern Minnesota forest

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ABSTRACT

Salvage logging after natural disturbance has received increased scrutiny in recent years because of concerns over detrimental effects on tree regeneration and increased fine fuel levels. Most research on tree regeneration after salvage logging comes from fire-prone systems and is short-term in scope. Limited information is available on longer term responses to salvage logging after windstorms or from forests outside of fire-prone regions. We examined tree and shrub regeneration after a stand-replacing windstorm, with and without salvage logging and prescribed fire. Our study takes place in northern Minnesota, USA, a region where salvage logging impacts have received little attention. We asked the following questions: (i) does composition and abundance of woody species differ among post-disturbance treatments, including no salvage, salvage alone, and salvage with prescribed burning, 12 years after the windstorm?; (ii) is regeneration of *Populus*, the dominant pre-blowdown species, inhibited in unsalvaged treatments?; and (iii) how do early successional trajectories differ among post-blowdown treatments? Twelve years after the wind disturbance, the unsalvaged forest had distinctly different composition and abundance of trees and woody shrubs compared to the two salvage treatments, despite experiencing similar wind disturbance severities and having similar composition immediately after the blowdown. Unsalvaged forest had greater abundance of shade tolerant hardwoods and lower abundance of *Populus*, woody shrubs, and *Betula papyrifera*, compared to salvage treatments. There was some evidence that adding prescribed fire after the blowdown and salvage logging further increased disturbance severity, since the highest abundances of shrubs and early successional tree species occurred in the burning treatment. These results suggest that salvage treatments (or a lack thereof) can be used to direct compositional development of a post-blowdown forest along different trajectories, specifically, towards initial dominance by early successional *Populus* and *B. papyrifera* with salvage logging or towards early dominance by shade tolerant hardwoods, with some *Populus*, if left unsalvaged.

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1. Introduction

Salvage logging has received increased scrutiny in recent years (Lindenmayer et al., 2004). Historically, salvage logging has been used to prevent economic losses following natural disturbance and is arguably successful for that purpose. It is also used to reduce post-disturbance fuel loads and for promoting forest regeneration and guiding successional development towards desired future conditions. While there is substantial evidence that salvage logging can be successful at meeting these latter goals (McIver and Starr, 2000), its appropriateness is still questioned (Lindenmayer et al., 2004; Greene et al., 2006). In fact, recent evidence suggests that salvage logging can actually increase fine fuels (Donato et al., 2006) and subsequent fire severity (Thompson et al., 2007) inhibit natural regeneration of trees (Van Nieuwstadt et al., 2001), and slow successional recovery (Lindenmayer and Ough, 2006).

Most research on tree regeneration and successional development after salvage logging has occurred in post-fire ecosystems in the western United States and Australia (McIver and Starr, 2000). Moreover, most studies examine only the short-term effects of salvage logging on ecosystem function (Lindenmayer and Noss, 2006). Much less information is available on long-term effects and feasibility after windstorms (Spurr, 1956; Sinton et al., 2000; Elliott et al., 2002; Peterson and Leach, 2008), and from forests of other regions. For instance, while relatively infrequent in time and space, meso- to large-scale windstorms are an important forest disturbance in many regions, such as the western Great Lakes region in the United States (Canham and Loucks, 1984; Reich et al., 2001; Hanson and Lorimer, 2007). Some speculate that these disturbances may be increasing in frequency as a consequence of

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climate change (Schelhaas et al., 2003). With increased frequency of wind disturbance in the future there may be an increased desire to salvage log after these disturbances.

Studies of tree regeneration and successional development after a single disturbance, wind or otherwise, are common. It is the relative rapid imposition of a second disturbance (e. g. salvage logging) after the first, which is much less studied. Some hypothesize that the cumulative effects of the combined disturbances lead to conditions outside of range of natural variation for native species and ecosystem function, with potentially deleterious effects (Lindenmayer et al., 2004; Lindenmayer and Noss, 2006; Peterson and Leach, 2008). Adding a third disturbance in rapid sequence likely results in even greater complexity or uncertainty of response, as for example when wind, salvage logging, and fire interact (e.g., Kulakowski and Veblen, 2007). There is virtually no research with a longer term perspective that allows generalization about vegetation responses to wind disturbance followed by salvage logging and prescribed fire.

The overall objective of our study was to examine tree and woody shrub regeneration patterns after a stand-replacing wind disturbance, with and without salvage logging and prescribed fire. Our study takes place in northern Minnesota, USA, a region where salvage logging impacts have received little attention, but where understanding the effects of natural disturbance and salvage logging on forest regeneration has been identified as a high priority research need (Mattson and Shriner, 2001). Specifically, our study includes wind-disturbed, but unsalvaged controls, replication of treatments, and longer term data, collected over a 12-year period. We addressed the following questions: (1) does composition and abundance of woody species differ among post-disturbance treatments 12 years after the original windstorm?; (2) is aspen regeneration inhibited in unsalvaged treatments?; (3) and how do early successional trajectories differ among disturbance treatments?

2. Methods

2.1. Study area

We conducted our study in the Trout Lake Roadless Area on the Chippewa National Forest, located in north central Minnesota, USA. The Trout Lake area is approximately 2740 ha and the forest is composed predominantly by *Populus tremuloides* (trembling aspen) and some *Populus grandidentata* (bigtooth aspen), with lesser amounts of other southern boreal transition species, including *Acer saccharum* (sugar maple), *Acer rubrum* (red maple), *Quercus rubra* (northern red oak), *Betula papyrifera* (paper birch), *Pinus resinosa* (red pine), and *Pinus strobus* (eastern white pine). At the time of disturbance, the majority of the forest was 65–70 years old, having initiated following logging and wildfires early in the 20th century. Upland soils throughout most of the study area are loamy sands and sandy loams derived from glacial outwash or till.

On July 13 1995, a severe summer windstorm swept across northern Minnesota in an easterly direction. The storm damaged approximately 152 ha in the Trout Lake area. Storm damage to the Trout Lake area was concentrated in 30 discrete blowdown patches. Patches averaged 5 ($\pm$5 sd) ha in size and ranged from 2 to 18 ha (Palik and Robl, 1999).

2.2. Study design

Nine of the 30 blowdown patches were salvaged logged during the summer of 1996, approximately 12 months after the windstorm. In late spring of 1997, five of the logged patches were prescribed burned. The purpose of the burning was to create seedbed conditions conducive to establishment of native conifer species, including *P. strobus*, *P. resinosa*, and *Picea glauca*. We sampled all salvaged logged and salvaged and burned patches and randomly selected six unsalvaged patches for sampling. Our study is an unplanned experiment in that we had no control over the assignment of treatments to patches (i.e., blowdown, salvage, prescribed fire) and thus we lack random assignment of treatments to experimental units.

2.3. Vegetation sampling

In spring 1996, prior to any salvage logging, we set up a series of permanent sampling points in each selected blowdown patch for vegetation sampling. In each patch, we located an initial point by selecting a random distance and compass bearing while standing at the approximate center of the patch. Additional points were located along the long axis of a patch by pacing randomly selected distances of at least 50 m from each subsequent point. The number of sample points in each patch ranged from four to 10 depending on patch size.

At each point we used variable radius (prism) plots to sample live residual trees (dbh $\geq$10 cm) and saplings (2.5 cm $\geq$ dbh $<$ 10 cm) within each blowdown patch. We took prism samples using a 10-factor (English unit) prism for trees and a 5-factor prism for saplings. At each point, we recorded the species and diameter of all live trees and saplings in the sample. At each of the sample points, we used the point-quarter method (Mueller-Dombois and Ellenberg, 1974) to sample trees that were uprooted or snapped off by the windstorm. In each quarter, we recorded the distance from the central point to the approximate center of the original bole location of the nearest uprooted or snapped tree, as well as its species identity and diameter at 1.4 m above the ground. We sampled tree regeneration and woody shrubs in subplots located around each tree sample point. One subplot was located at plot center and four were centered on points located 5 m from the center point in cardinal compass directions (N,S,E,W). Small stems ($<$1 m tall) were sampled in 1 m^2 quadrats, while larger stems ($\geq$1 m tall and $<$2.5 cm dbh) were tallied in 3.14 m^2 circular plots.

Vegetation was first sampled in the summer of 1996, approximately 12 months after the blowdown, but before salvage logging that began in late summer of that year. This sampling was repeated in the spring of 1997, before prescribed burning, largely to document the direct physical effects of salvage logging on stand structure and regeneration. Sampling was repeated in summer 2001, four years after the prescribed burning and again in the summer 2007, 12 years after the blowdown, 11 years after salvage logging, and 10 years after prescribed fire. For most response variables, only initial post-blowdown, but pre-salvage data, and 10–12 year post-blowdown data are reported here.

2.4. Analysis

Overstory tree diameter data (stems $\geq$10 cm dbh) for both live and dead trees were summarized into species basal areas and used to reconstruct pre-blowdown forest composition (summing residual and dead basal areas by species) and immediate post-blowdown composition (residual trees). Patch-scale basal areas were used to assess disturbance severity among treatments based on changes in basal areas after blowdown and salvage logging. Similar to the approach outlined in Peterson and Leach (2008), we quantified disturbance severity among the three treatment groups (unsalvaged, salvaged, salvaged and burned) based on (1) the amount of basal area removed by the windstorm and (2) the cumulative basal area removed by the windstorm and subsequently salvaged, as well as additional live basal area lost during salvage to harvesting and mortality of residual trees.

Plot level regeneration abundance data were summarized to the blowdown patch-scale for each measurement year. Stems $<$1 m

Table 1
Pre- and post-blowdown forest composition (trees >10 cm diameter).

Species	Pre-blowdown[a] (m²/ha)	Post-blowdown[b] (m²/ha)
Populus spp.[c]	32.2 (9.7)[d]	4.2 (2.6)
Betula papyrifera	1.5 (1.2)	0.8 (0.8)
Pinus[e]	2.0 (2.3)	0.8 (1.3)
Shade tolerant hardwoods[f]	2.7 (1.7)	1.0 (0.9)
Mid-tolerant hardwoods[g]	0.7 (0.8)	0.8 (0.8)
Other conifers[h]	0.3 (0.9)	0.0 (0.0)
Total	39.5 (9.0)	7.3 (3.1)

[a] Combined basal area of blowdown and residual trees.
[b] Basal area of residual trees before salvage logging.
[c] *P. grandidentata* and *P. tremuloides*.
[d] Values are means (+1 standard deviation) of 15 patches.
[e] *P. resinosa* and *P. strobus*.
[f] *A. saccharum*, *A. rubrum*, *Tilia americana*, *Ostrya virginiana*.
[g] *Q. rubra*, *Quercus macrocarpa*, *Fraxius nigra*.
[h] *P. glauca* and *Abies balsamea*.

tall and >1 m but <2.5 cm diameter were pooled for analyses since the majority of individuals for all species were in the larger size class and examining them separately did not change the results. For the ANOVA analysis described next, individual species were pooled into six species groups to reduce noise in the data, including *Populus*, *B. papyrifera*, mid-tolerant hardwoods, shade tolerant hardwoods, *Pinus*, and woody shrubs (see Table 1 for species included in each group). A single factor fixed effect ANOVA model was used to test for overall treatment effects on basal area values and regeneration densities by species group, followed by orthogonal contrasts if the overall model was significant. Specific contrasts included (1) unsalvaged versus salvaged and salvaged and burned and (2) salvaged versus salvaged and burned. Data distributions were checked for normality and homogeneity of variances and transformed as necessary. Differences in treatment means were considered significant at $p = 0.05$.

Nonmetric multidimensional scaling was used to graphically display and interpret woody community compositional differences within the regeneration layer (all stems <2.5 cm dbh) among treatments for the 12th year data. The data matrix consisted of blowdown patches (rows) and woody species that occurred in at least five patches (columns). NMS relaxes assumptions of normality and linear relationships to environmental variables, provides a biologically meaningful view of data, and preserves distance properties among sample units (blowdown patches, in our case) (Clark, 1993; McCune and Grace, 2002). We used Sorenson (Bray–Curtis) distance measures, and specified 6 dimensions and 250 iterations (with actual data) for the initial analysis. Significance of dimensional solutions was assessed using Monte Carlo permutation procedures (based on 249 interactions). Our final ordination was restricted to 3 dimensions based on stress reduction and examination of scree plots (McCune and Grace, 2002).

Following NMS, we used a multi-response permutation procedure (MRPP, Biondini et al., 1988) to identify differences among treatments groups suggested by the NMS ordination. MRPP is a nonparametric procedure useful for comparisons among previously defined groups of sampling units (McCune and Grace, 2002). We ran MRPP using a Euclidean distance measure. Following the overall test, we performed pairwise comparisons to clarify differences among treatment groups. All multivariate procedures were performed using PC–ORD 5.0 software (McCune and Mefford, 2006). For all statistical tests associated with multivariate procedures, $p = 0.05$ was considered significant.

3. Results

3.1. Pre- and post-blowdown overstory composition

Before blowdown, the overstory (trees ≥10 cm dbh) of the disturbed patches was dominated by *P. grandidentata*, with some *P. tremuloides*, which combined accounted for 82% of total basal area (Table 1). Shade tolerant hardwood species accounted for another 7% of total basal area, followed by *P. resinosa* and *P. strobus* (5%), *B. papyrifera* (<4%), mid-tolerant hardwood species (<2%), and other conifers (<1%) (Table 1). The overstory of the post-blowdown patches (before salvage logging) was still dominated by Populus (57% of total basal area) (Table 1), with lesser amounts of shade tolerant hardwoods (14%), *Populus* and *B. papyrifera* (11% each), and mid-tolerant hardwoods (7%).

3.2. Disturbance severity based on basal area changes

Pre-blowdown basal areas (summing dead and live residual trees) were not significantly different among the three treatment groups ($p = 0.217$), ranging from 36 to 46 m²/ha (Table 2, row A). After the blowdown, but before salvage logging, residual basal areas in disturbed forest patches averaged around 7 m²/ha and did not differ significantly among the future post-blowdown treatment groups ($p = 0.763$; Table 2, row B). The amount of basal area that was blowndown ranged from 28 to 39 m²/ha and also did not differ significantly among treatment groups ($p = 0.221$; Table 2, row C). The salvage treatments essentially removed all uprooted and snapped trees from the disturbance patches (Table 2, rows C and D are equal for the salvaged treatments). Additionally, the two salvage treatments were associated with additional declines in live tree basal area (Table 2, row E), presumably due to harvest of some live (but dying) trees or additional mortality of residual trees in these treatments after salvage. However, after salvage, residual basal areas still were not significantly different among the treatment groups ($p = 0.066$; data not shown).

Cumulative basal area removed by blowdown and salvage was estimated by summing together the amount of basal area blowdown, the amount of basal area salvaged, and the additional live basal area lost after salvage (Table 2; row G). This value was by default significantly higher for the two salvaged treatments than the unsalvaged treatment ($p = 0.0002$), but did not differ between the former two treatments themselves ($p = 0.355$; Table 2, row G).

Table 2
Basal area values (m²/ha) of unsalvaged, salvaged, and salvaged and burned treatments after blowdown in northern Minnesota, USA. Values are means (± se). Means in a row followed by different letters were significantly different at $p = 0.05$.

	Unsalvaged	Salvaged	Salvaged and burned
(A) Pre-blowdown basal area	35.5 (3.0)a	45.7 (5.4)a	39.4 (3.5)a
(B) Post-blowdown basal area	7.5 (1.1)a	6.8 (2.8)a	6.0 (0.8)a
(C) Basal area blowndown	27.9 (2.7)a	38.9 (6.3)a	33.4 (4.0)a
(D) Blowndown basal area salvaged	0.0 (0.0)a	38.9 (6.3)b	33.4 (4.0)b
(E) Live basal area removed by salvage	0.0 (0.0)	2.0 (1.8)b	2.4 (0.7)b
(F) Cumulative basal area removed by wind and salvage*	27.9 (2.7)a	79.7 (12.4)b	69.2 (7.4)b

* The sum of basal area blowdown, plus blowndown basal area removed by salvage (assumes all blowdown basal area was salvaged), plus live basal area removed or lost due to salvage.

Prescribed burning likely killed some additional trees in the residual overstory, but we did not sample in a way that would detect this mortality.

3.3. Regeneration responses

3.3.1. Post-blowdown

One year after the blowdown, but before any salvage logging or burning, densities of *Populus*, *B. papyrifera*, *Pinus*, mid-tolerant and shade tolerant hardwoods and woody shrubs in the regeneration layer (dbh <2.5 cm) did not differ significantly among patches assigned to the future treatment groups ($p > 0.1$ for all groups; Fig. 1). Woody shrubs dominated this layer, followed by shade tolerant hardwoods and *Populus*.

3.3.2. Post-salvage/pre-burning and post-burning

Tree and shrub densities in the regeneration layer after salvage logging but before burning largely reflected decreases in abundance from physical impacts to existing vegetation in the salvaged and salvaged and burned treatments, since less than a full growing season separated salvage logging from our pre-burn sampling (data not shown). For example, densities of shade tolerant hardwoods were reduced, compared to pre-salvage densities, as were mid-tolerant hardwoods, woody shrubs, and *Populus* in the salvaged and burned treatment (data not shown). Our initial post-burn sampling occurred four years after the burning treatment. By this time, patterns in regeneration responses (data not shown) largely paralleled responses detected after 12 years (see Section 3.3.3 below).

3.3.3. Twelve-year responses

Regeneration response after 12 years revealed several trends reflective of a gradient of compounding treatment effects with the addition of disturbances (Fig. 2). Densities of *Populus* suckers, as well as *B. papyrifera* and woody shrubs, were significantly higher in the two salvage treatments compared to the unsalvaged treatment ($p = 0.017$, 0.0008, and 0.0002, respectively), while density of *Populus* in the salvaged and burned treatment was significantly

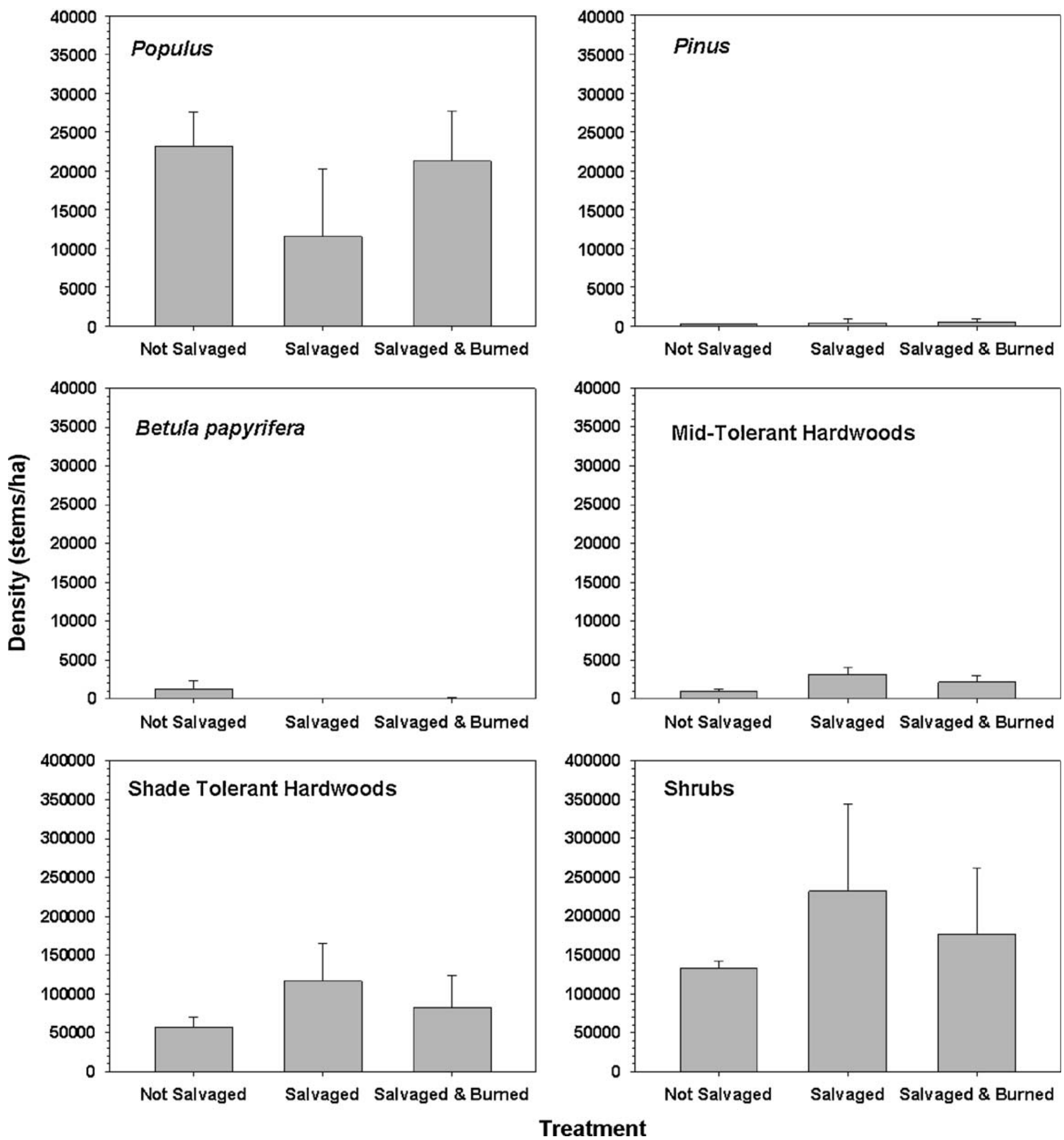

Fig. 1. Density of woody regeneration (stems <2.5 cm diameter at 1.4 m height) in major species groups after blowdown, but before salvage logging. See Table 1 for a list of species within species groups. Note the change of *y*-axis-scale for the bottom two frames. There were no significant differences among treatments for any of the taxonomic groups.

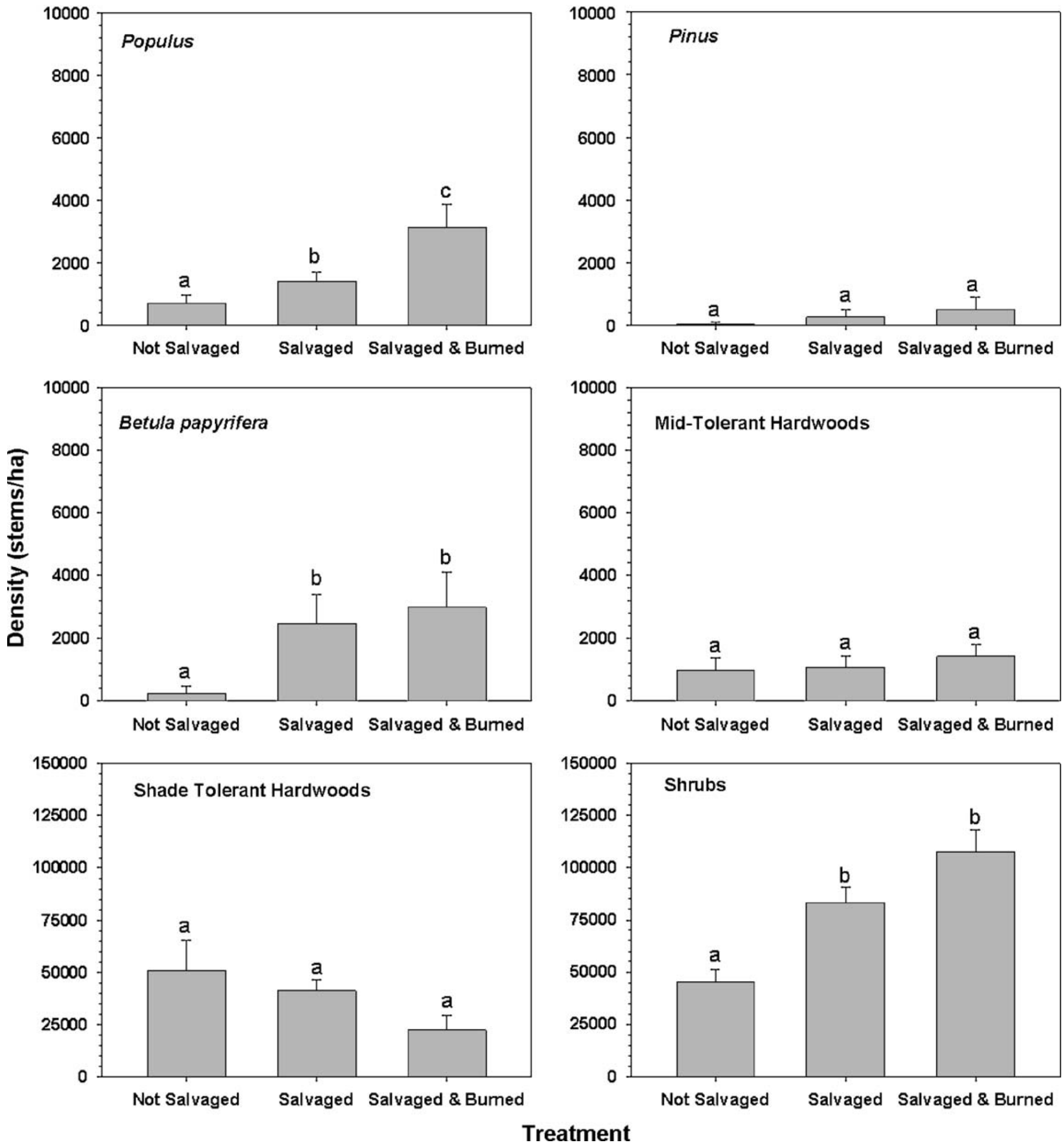

Fig. 2. Density of woody regeneration (stems <2.5 cm diameter at 1.4 m height) in major species groups 12 years after blowdown, 11 years after salvage logging, and 10 years after prescribed burning. See Table 1 for a list of species within species groups. Note the change of *y*-axis-scale for the bottom two frames. Different letters above treatment bars within a taxonomic group indicate significant differences at $p = 0.05$.

higher than the salvaged only treatment ($p = 0.033$). Densities of shade tolerant hardwoods declined across the disturbance gradient, but there were no significant differences among treatments ($p = 0.109$). Densities of *Pinus* and mid-tolerant hardwoods did not differ among treatments ($p = 0.632$ and 0.681, respectively).

By 12 years after the blowdown, substantial numbers of *Populus* suckers had recruited into the sapling size class (2.5 cm > dbh < 10 cm). Densities of these suckers were significantly higher in the salvaged and salvaged and burned treatments compared to the unsalvaged treatment ($p = 0.02$), but the two salvage treatments did not differ ($p = 0.54$; Fig. 3). There were low densities of saplings for other taxonomic groups and no significant differences among treatments for these groups (Fig. 3).

The NMS ordination converged on a three axes solution and explained 95 percent of variation in compositional data among patches. Final stress was 5.25, and final instability was 0.0004. Axes 1 and 3 accounted for most variation (69%; Fig. 4). There was clear separation of the unsalvaged patches from the other two treatment groups. Further, there was some separation of the salvaged and salvaged and burned treatment patches on axis 3 (Fig. 4). Axis 2 (not shown) accounted for 26% of total variation, but patterns among the three treatment groups on this axis largely paralleled those on axis 3, indicating that variation on axis 2 was largely related to differences among patches within treatment groups.

Several species had high correlations ($r \geq 0.7$) with the NMS axes (Table 3) and were strongly associated with blowdown patches within a treatment group (Fig. 4). *A. saccharum* was highly correlated with axis 3 ($r = 0.909$) and the shrub *Dirca palustris* was negatively correlated with axis 1 ($r = -0.757$); both taxa were associated with unsalvaged blowdown patches (Fig. 4). *Populus* ($r = 0.802$), *B. papyrifera* ($r = 0.755$), and *Rubus* ($r = 0.878$) were positively correlated with axis 1 and associated with salvaged and salvaged and burned treatments (Fig. 4). Finally, *A. rubrum* ($r = -0.725$) and *Lonicera canadensis* ($r = -0.835$) were both

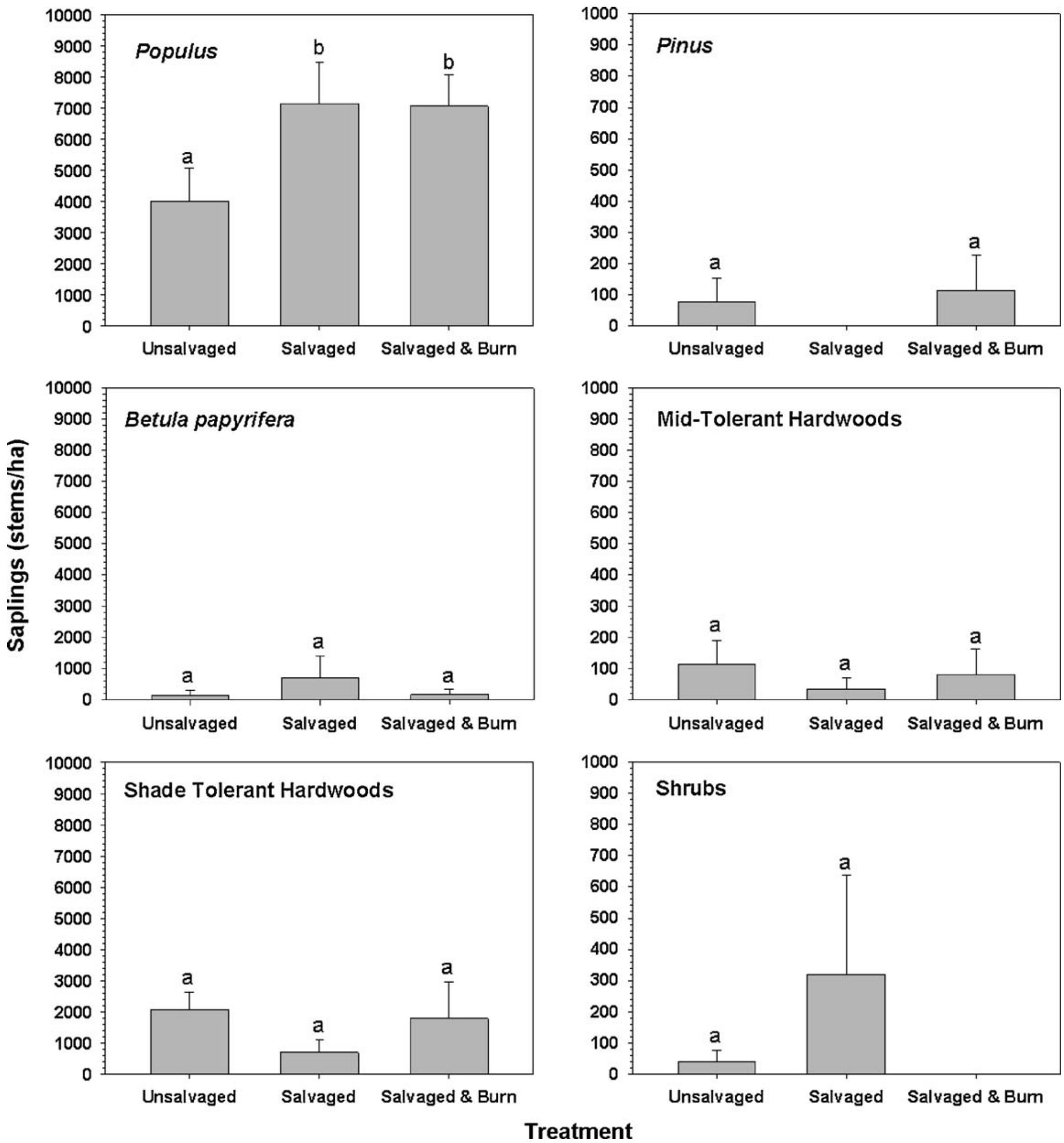

Fig. 3. Density of saplings (stems ≥2.5 cm but <10 cm diameter at 1.4 m height) in major species groups 12 years after blowdown, 11 years after salvage logging, and 10 years after prescribed burning. See Table 1 for a list of species within species groups. Note the change of *y*-axis-scale for the frames on the right. Different letters above treatment bars within a taxonomic group indicate significant differences at $p = 0.05$.

negatively correlated with axis 3 and served to differentiate salvaged from salvaged and burned treatments to some degree.

The MRPP found less heterogeneity of species communities within salvage treatment groups, and more heterogeneity among groups, than expected by chance ($T = -3.36$, A = 0.140, $p = 0.004$), indicating that treatment groups differed from each other. Pairwise comparisons confirmed this, as the woody species community of the unsalvaged treatment was significantly different than both the salvaged ($p = .041$) and salvaged and burned treatments ($p = 0.008$). The latter two treatments were not significantly different ($p = 0.087$).

4. Discussion

Our study documents longer term responses of woody vegetation development in a southern boreal transition forest following stand-replacing wind disturbance with and without salvage logging and prescribed burning. As reflected in the 12th year NMS (Fig. 4, Table 3) and MRPP results, the disturbed, but unsalvaged forest, had distinctly different composition of woody plants compared to the salvaged forest, despite experiencing similar wind disturbance severity (based on reduction in basal area) and having an immediate post-blowdown composition that was largely the same among the treatment groups (Fig. 1). Specifically, by 12 years, the two salvage treatments had higher densities of *Populus*, *B. papyrifera*, and woody shrubs compared to the unsalvaged forest (Figs. 2–4), while the latter had higher densities of shade tolerant hardwoods (Figs. 2 and 4); results supported by the strong correlations of these species groups with the NMS axes (Table 3). Our results of higher shrub densities in salvaged treatments contrasts to those of Stuart et al. (1993) who found lower shrub densities in salvaged Douglas-fir/hardwood forests after wildfire.

The compositional differences reflect differences in cumulative disturbance severity (based on basal area reduction and removal) between salvaged and unsalvaged treatments (Table 2, row F).

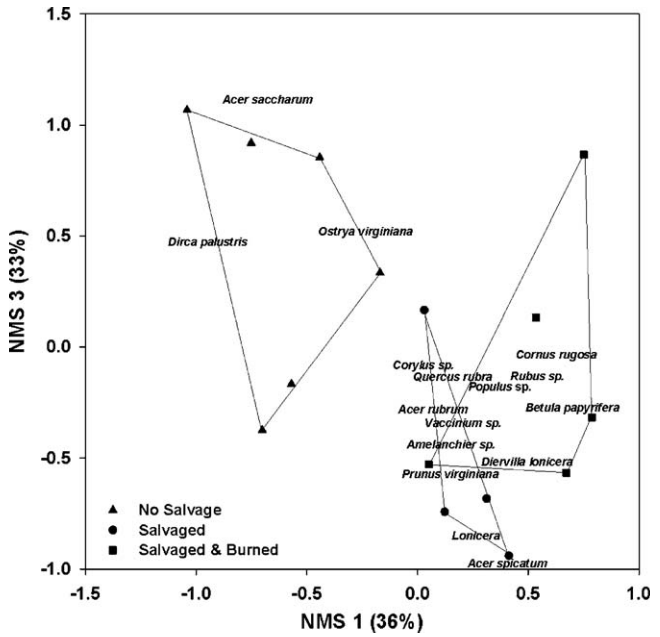

Fig. 4. Non-metric, multidimensional scaling ordination biplot of treatment stands and woody species 12 years after blowdown, 11 years after salvage logging, and 10 years after prescribed burning.

Table 3
Summary of correlations between plant species in blowdown patches and the first and third NMS axes.

Taxa	*r*-Values	
	Axis 1	Axis 3
Populus spp.	0.802	−0.305
Betula papyrifera	0.755	−0.330
Acer rubrum	0.173	−0.725
Acer saccharum	−0.627	0.909
Ostrya virginiana	−0.263	0.396
Quercus rubra	0.395	−0.230
Acer spicatum	0.303	−0.649
Amelanchier spp.	0.317	−0.613
Cornus rugosa	0.610	−0.026
Corylus spp.	0.173	−0.410
Diervilla lonicera	0.437	−0.538
Dirca palustris	−0.757	0.336
Lonicera canadensis	0.312	−0.835
Prunus virginiana	0.278	−0.660
Rubus spp.	0.878	−0.225
Vaccinium spp.	0.413	−0.551

Salvage logging after the wind disturbance greatly increased cumulative disturbance severity, since essentially all of the blowndown trees were removed and additional live trees were removed or died after salvage. We did not measure changes in the forest floor or mineral soil resulting from salvage logging (or prescribed fire). Since the logging took place in the summer growing season, such changes likely occurred and were presumably important components contributing to differences in disturbance severity, and vegetation response, between salvaged and unsalvaged treatments (Roberts, 2007).

There was some evidence that fire altered compositional dynamics even more than wind and salvage alone, since the highest densities of *Populus*, woody shrubs, and *B. papyrifera*, and the lowest densities of shade tolerant hardwoods, were found in salvaged and burned treatments (Figs. 2–4). However, for most species groups, the differences between salvaged and burned and salvaged only treatments were small, which is consistent with the similar cumulative disturbance severity indices (prior to burning) for the two treatments (Table 2, row F). We were not able to sample the overstory immediately after prescribed burning; it is likely that some additional mortality of overstory trees occurred as a result of the burning that is not captured in our measure of basal area reduction. Moreover, burning may have altered understory plant communities directly through mortality to established tree regeneration and shrubs and by altering seedbed conditions, forest floor temperatures, and nutrient availability (DeLuca and Zouhar, 2000).

We did find significantly reduced densities of *Populus* vegetative suckers in the unsalvaged treatment, compared to the two salvaged treatments (Figs. 2 and 3). This may have resulted from several factors, including lower soil heating in the unsalvaged treatment, due to shading from downed boles, resulting in fewer total degree days of optimal temperatures for sucker initiation (Frey et al., 2003). In addition, the shading from these downed boles likely limited the light availability to this shade intolerant taxon. Finally, growth regulator inhibition of new sucker initiation (Frey et al., 2003) potentially may have occurred on root systems still attached to live standing parent stems in the unsalvaged treatment. Alternatively, sucker initiation may have been higher in the two salvaged treatments due to higher soil warming with greater mineral soil exposure and in the salvaged and burned treatment due to greater soil warming after fire (Frey et al., 2003).

Our results all point to distinct successional trajectories among treatments, specifically, initial dominance by intolerant, early successional species with salvage logging versus early dominance by shade tolerant hardwoods without salvage logging. Other studies also have documented greater abundance of intolerant species in salvaged logged treatments (Spurr, 1956; Sinton et al., 2000; Greene et al., 2006; Peterson and Leach, 2008). In our study, the increased abundance of early successional species was a direct consequence of the salvage treatments, as opposed to pre-blowdown differences in composition, as found by others (Peterson and Leach, 2008), since composition did not differ among treatment groups after blowdown but before logging (Fig. 1). The high woody shrub densities in the salvaged treatments potentially may continue to competitively inhibit establishment of later successional tree species in the salvaged treatments overtime (Dovciak et al., 2003; Weyenberg et al., 2004).

4.1. Management application

One justification for salvage logging is to create opportunities for regeneration and restoration of desired tree species. With this in mind, one of the stated goals of salvage logging in the environmental assessment of the Trout Lake area was to create mineral seedbeds for *P. resinosa* and *P. strobus* establishment, since the historical forest composition, based on bearing tree analysis, indicated dominance by a mixed pine-hardwood forest (Chippewa National Forest, 1996). While there was a non-significant increase in *Pinus* densities from unsalvaged to salvaged to salvaged and burned treatments by the 12th year of the study (Fig. 2), overall *Pinus* densities in the regeneration layer were very low and do not appear to have been greatly influenced by the post-blowdown treatments. These results indicate that salvaging alone, or with a single prescribed fire, may not be sufficient to meet compositional objectives without additional activities to facilitate establishment of desired species.

The lack of regeneration of *Pinus* may have been at least partially related to limited seed sources in the disturbed patches (Table 1). However, most of these residual trees were large canopy dominants or super-dominants and likely dispersed seed over large distances (Palik and Pregitzer, 1994). Moreover, there where somewhat higher densities of these large individuals scattered throughout the undisturbed forest (see Table 1, pre-disturbance composition) that likely also were potential seed sources. Other factors that may have inhibited *Pinus* establishment in disturbed patches included excessive browsing from whitetail deer (Ross et al., 1970; Saunders and Puettman, 1999), and poor seedbed conditions even in the salvaged and salvaged and burned treatments.

The historical natural disturbance regime of the forest types of Trout Lake study area consisted of frequent surface fires (~25 years) and infrequent and more intense crown fires (~150–200 years) (Heinselman, 1973, 1981). This fire regime was responsible for maintenance of *Pinus* in the landscape. In contrast, the contemporary disturbance regime is characterized by a near total absence of wildfire and low intensity and small spatial-scale of prescribed fire (when it is used). Consequently, fire sensitive hardwood species dominate the contemporary landscape. The result is a landscape and forest condition that is not very fire-prone. As such, reduction of fuels and fire risk in scattered patches of blowdown within a matrix of fire resistant forest may not necessarily be a valid justification for salvage logging in this type of landscape. Nevertheless, our results do suggest that salvage treatments (or a lack thereof) can be used to direct compositional development of a post-blowdown forest along different trajectories as established by the boundary compositional conditions that currently exist in the contemporary landscape.

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