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Trembling Aspen Stand Response 15 Years after Windthrow, Salvage Harvesting, and Forest Renewal

Rongzhou Man * and Mya Rice

Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry, Ontario Forest Research Institute, 1235 Queen Street East, Sault Ste. Marie, ON P6A 2E5, Canada; mya.rice@ontario.ca
* Correspondence: rongzhou.man@ontario.ca

Abstract: Windthrow is a common occurrence in boreal forests, affecting wood supply and presenting regeneration challenges for forest managers. Salvage harvesting is often conducted afterwards to extract valuable wood and improve access for forest renewal activities. Research efforts, however, are generally limited to the effects of windthrow and salvage harvesting in the first few years following disturbance. In 2006, a catastrophic wind event occurred in a trembling aspen (*Populus tremuloides* Michx.) forest in northeastern Ontario. A field study was established with a range of silvicultural treatments from leaving after windthrow (W) to forest renewal treatments including windrow site preparation, planting, and herbicide release (WSPR). While the results of first 5-year assessment have been reported, the objective of the current study was to reassess treatment effects at 15 years post-disturbance, a stage of stand development that is more indicative of future forest conditions. Compared to the results of the earlier assessment, the 15-year assessment indicated that standing dead wood (snags) declined, whereas coarse downed wood did not change substantially over time. Post-disturbance salvage harvesting improved aspen regeneration in terms of density, stocking, and growth, but substantially reduced the proportion of conifers relative to windthrow only. Thus, salvage harvesting helped to sustain aspen composition, compared to other treatment options that increased proportions of pine and spruce trees from W to windthrow and salvage harvesting combined with windrow site preparation and planting (WSP), and from WSP to WSPR.

Keywords: *Populus tremuloides*; windthrow; salvage; snags; downed wood; regeneration

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1. Introduction

In North American boreal mixedwood forests, wind disturbance affects stand structure and dynamics at different scales and levels of intensity [1–4]. With a catastrophic windthrow event, the overstory can be largely depleted, for example, by stem breakage of trembling aspen (*Populus tremuloides* Michx.) and uprooting of black spruce (*Picea mariana* (Mill.) BSP.), white spruce (*P. glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), and balsam fir (*Abies balsamea* (L.) Mill.) [5–7]. Post-disturbance stands are characterized by large quantities of standing dead (snags) and downed wood [4,7,8]. Sub-canopy white birch (*Betula papyrifera* Marsh.) and advanced spruce and fir in the understory may survive [7,8] as structural legacies of the pre-disturbance forest [9,10], thereby increasing later successional, shade tolerant conifers in stands dominated by trembling aspen. However, quantitative data are needed to verify this successional trajectory [7].

Windthrow reduces the aspen overstory releasing sub-canopy and understory trees [7,8] and pits and mounds formed by uprooted trees act as seedbeds for regenerating trees and vegetation [11,12]. Additionally, the overstory reduction is similar to that created by a clearcut harvest in that it reduces apical dominance and increases light and temperature promoting vegetative aspen regeneration [7,13–16]. The influences of post-windthrow residual trees, standing dead trees, and downed wood on the density, stocking, and growth of aspen regeneration have been rarely quantified nor has the response of understory trees and vegetation to a catastrophic wind event.

Catastrophic windthrow is often followed by salvage harvesting to recover valuable wood [7–9], to reduce fuel loads and thus fire risk [17–19], and to improve access for forest renewal activities [7,9]. While logging disturbance can increase the availability of seedbeds [20–22], the operation may damage regeneration—both the advanced understory trees [7,9,22,23] and post-disturbance natural regeneration [16,24]—as well as disrupting other forest attributes including deadwood and biodiversity [25]. Reported findings on salvage harvesting are generally short-term [17,22,24,25] and do not extend to combined effects with post-disturbance forest management practices (e.g., site preparation, planting, and release) used to restore forests [7].

In July 2006, a severe windthrow disturbance occurred in a 3 km × 11 km area, about 110 km southwest of Kapuskasing, Ontario (48°39′ N to 48°41′ N; 83°02′ W to 83°05′ W). To investigate post-disturbance forest recovery, a field study was established with a series of silvicultural treatments: leaving after windthrow (W), operational salvage harvesting (S), and salvage harvesting combined with windrow site preparation, planting (P), and herbicide release (R). Residual overstory volume and density, snag volume and density, and coarse downed wood volume were surveyed at treatment plot establishment, 2–4 years post-windthrow, and regeneration density, height, and stocking, and vegetation and coarse and fine downed wood cover were assessed at treatment plot establishment, as well as 5 years post-windthrow. Five years after windthrow, 30% removal of stand volume improved aspen regeneration but also damaged the advanced regeneration, mostly black spruce and balsam fir [7]. Windrow site preparation reduced the area covered by coarse downed wood, while herbicide release reduced the abundance of broadleaf regeneration and shrubs and increased the survival and growth of planted spruce trees and grass abundance. Findings indicated that a windthrow event followed by immediate salvage harvesting is a viable option for promoting aspen regeneration, but, if conifer stands are desired, forest renewal treatments are needed to improve conifer stocking and growth. Early assessments also showed highly temporal dynamics in downed wood and vegetation cover, and regeneration density and height from treatment plot establishment to 5 years post-windthrow, and some of these temporal changes differed among treatments, i.e., significant treatment by time interactions. This suggests that early findings likely change over time and may not indicate future forest conditions. Longer-term surveys are therefore required for assessing treatments effects and post-windthrow stand dynamics. The current study is based on 15-year post-windthrow assessments at a stage of stand development that is more indicative of future forest conditions [26]. The study objective is to assess treatment effects and stand attributes at longer-term silvicultural treatments, and evaluate temporal changes and implications to future forest conditions.

2. Materials and Methods

2.1. Study Area

Field plots were established after the 2006 catastrophic windthrow, salvage harvesting, and forest renewal operations [7]. Most pre-disturbance stands were mature trembling aspen, with some aspen and black spruce mixedwoods. Typical tree responses to the 120 to 150 km h^{-1} winds were the snapping or twisting off of aspen stems 2 to 8 m aboveground while conifers, mostly black spruce, were uprooted. The operational salvage logging was carried out in winter in select areas of pure aspen (≥80% basal area) in 2006–2007 and 2007–2008 to recover merchantable aspen, spruce, and jack pine and to improve access for forest renewal activities. The windthrown stands salvage logged in winter 2006–2007 were site prepared by windrowing debris and planted with black spruce and white spruce. To further emulate typical Canadian boreal mixedwood renewal strategies [27], some of the planted areas were aerial sprayed with glyphosate with intent to improve spruce survival and growth.

The study stands originated naturally from a large 1924 wildfire and were ≥80% trembling aspen (in basal area) with variable amounts of balsam poplar (*Populus balsamifera* L.), white birch, black spruce, white spruce, and jack pine. Based on the Ontario ecosite classification system, the pre-windthrow stands were aspen–birch broadleaves on fresh, silty to fine loamy, and moist, silty to fine loamy to clayey sites [28]. The soils are of the Brunisolic order, based on the Canadian soil classification system and Cambisols by the World Reference Base for Soil Resources [29]. At time of site reconnaissance in the fall of 2006, tall shrubs were predominantly mountain maple (*Acer spicatum* Lam.) and beaked hazel (*Corylus cornuta* Marsh.) [7]. Common low understory species included dwarf raspberry (*Rubus pubescens* Raf.), wild red current (*Ribes rubrum* L.), twinflower (*Linnaea* borealis L.), bush honeysuckle (*Diervilla lonicera* Mill.), naked miterwort (*Mitella nuda* L.), wild sarsaparilla (*Aralia elata* (Miq.) Seem.), bunchberry (*Cornus canadensis* L.), wild lily-of-the-valley (*Maianthemum canadense* Desf.), and feather mosses (*Hylocomium* spp.) [7].

2.2. Experimental Design

The 15-year post-windthrow assessments, conducted in the same measurement plots, established the following treatments in the complete randomized design described in detail by Man et al. [7]. The 5 treatments areas were established after the windthrow in 2006: Windthrow (W), untreated; Windthrow–Salvage (WS), windthrow followed by salvage logging in winter 2007–2008; Windthrow–Salvage–Plant (WSP), windthrow followed by salvage logging in winter 2006–2007, windrowing then 2007 planting of 1750 to 1800 seedlings ha^{-1} with mixed 25% black spruce and 75% white spruce; Windthrow–Salvage–Plant–Release (WSPR), windthrow followed by salvage logging in winter 2006–2007, windrowing then 2007 planting of 1750 to 1800 seedlings ha^{-1} with mixed 25% black spruce and 75% white spruce, and herbicide release with 2008 aerial spray of glyphosate; and Clearcut ©, a nearby 2005 clearcut with full tree harvesting and no additional treatments. Each of the treatments were replicated 5 times, with experimental units ranging from 1 to 2 ha with a minimum 30 m buffer from stand edge.

2.3. Standing and Downed Wood Surveys

In each of the 25 experimental units, live trees and standing dead stems (snags) were assessed in 3 circular overstory plots of 11.28 m radius, with at least 40 m between plot centres. The original overstory survey included trees $\geq$ 4 m in height [7]. The year 15 re-assessment added an additional threshold of diameter at breast height (DBH) $\geq$ 10 cm to exclude post-disturbance regeneration that was captured in the regeneration assessments. All live overstory trees and standing snags ($\geq$0.5 m in height) were tallied for species, DBH, and height. Some snags were decayed such that species identification was limited to broadleaf or conifer. Honer et al.'s equations [30] for central and eastern Canada were used to calculate the volume of overstory trees, while snag volume was calculated as a cylinder with diameter (diameter at breast height) and length (snag height), as suggested by Man et al. [7].

Coarse downed wood was surveyed along three 11.28 m transects emanating from the overstory plot centres. The azimuth of the first transect was randomly selected with the second and third transects at increments of 120°. Using the criteria outlined in Hayden et al. [31], coarse wood species, decay class, and diameter at the transect intersection midpoint were recorded for each piece $\geq$ 7.5 cm in diameter. Down coarse wood in decay classes 4–5 was often difficult to identify as a certain species or even as a species group, leaving some pieces unidentified. Coarse wood volume was determined using the method described by Van Wagner [32].

2.4. Regeneration and Vegetation Assessments

A line-plot method was used to assess regeneration and vegetation in July–August 15 years post-windthrow [7]. Lines were parallel to the long axis of the survey area or perpendicular to windrowed slash piles in treatments WSP and WSPR. All experimental units had 27 circular survey plots, established along a minimum of 3 parallel survey lines more than 20 m apart at 10 m intervals. Each 4 m^2 survey plot was used to measure tree species, height, and DBH of regenerating seedlings and saplings (height $\geq$ 2 cm and

DBH < 10 cm), and assess the ground cover of downed wood and vegetation. Percent cover was recorded for coarse downed wood (≥7.5 cm in diameter for downed woody material and stumps <2 m height), fine downed wood (<7.5 cm in diameter, mainly small trees and fine branches), shrubs, herbs, ferns and allies, grasses and sedges, mosses, and lichens. Regeneration stocking was calculated as the percentage of regeneration plots with at least 1 crop tree.

2.5. Data Analysis

Data analysis followed a completely randomized design with 5 replications. The analysis of variance (ANOVA) linear mixed effects (LME) model, available in *nlme* package, was used to compare differences in overstory live tree volume and density, snag volume and density, coarse downed wood volume, percent cover of grouped vegetation and coarse and fine downed wood, and regeneration density, stocking, height, and diameter among 5 post-windthrow treatments. Data were transformed when necessary to achieve normality based on a visual assessment and Shapiro–Wilk's test of residuals. Multiple contrasts of means among treatments were performed using Tukey HSD test with *p* values adjusted with Shaffer method available in *multcomp* package. All analyses were implemented using R version 4.1.2 [33].

3. Results

3.1. Overstory Trees and Snags

The volume of overstory trees ranged from 2.5 m^3 ha^{-1} in WSPR to 15.2 m^3 ha^{-1} in W, and overstory density ranged from 70 stems ha^{-1} in WSP to 185 stems ha^{-1} in W (Figure 1a,b). While both overstory volume and density did not differ significantly among the treatments (p = 0.382 and 0.253, respectively), overstory trees were mostly trembling aspen in WS and C, spruce trees in WSPR, jack pine in WSP, and balsam fir in W.

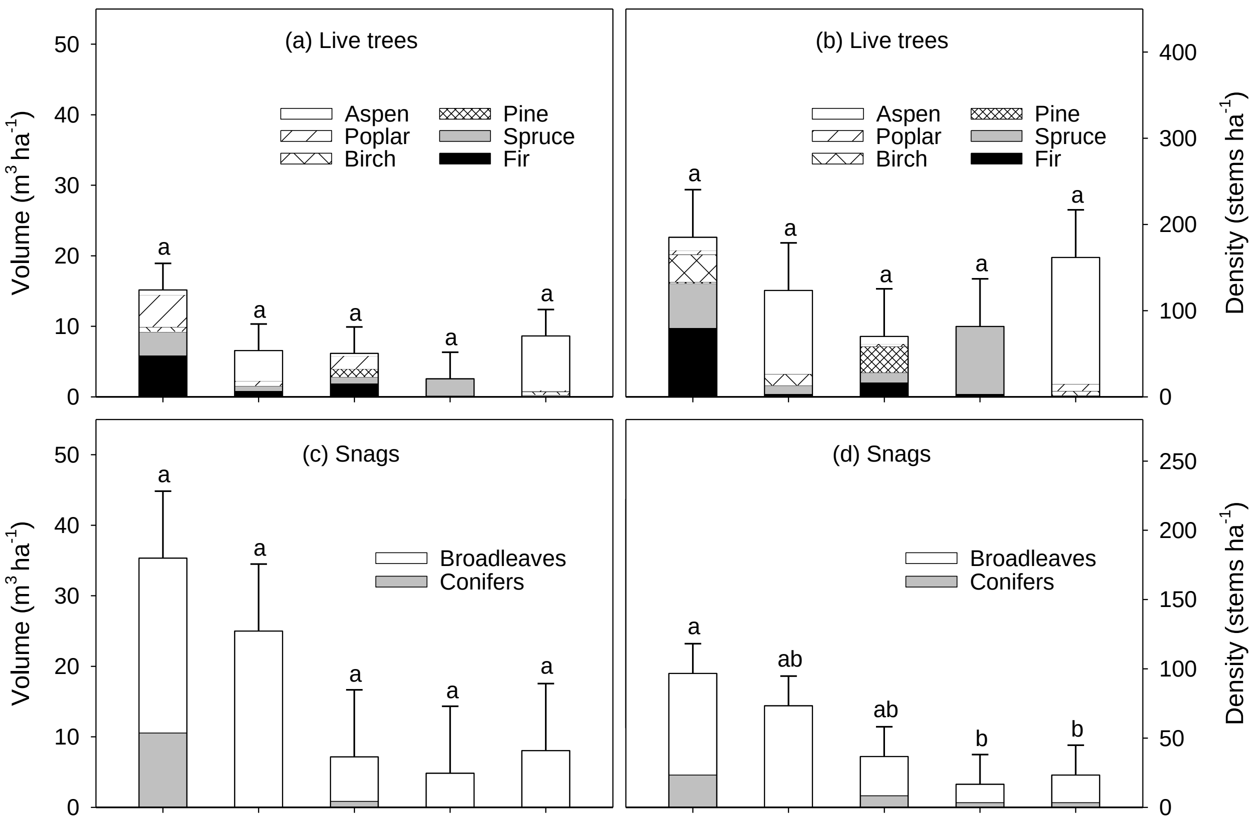


Figure 1. *Cont.*

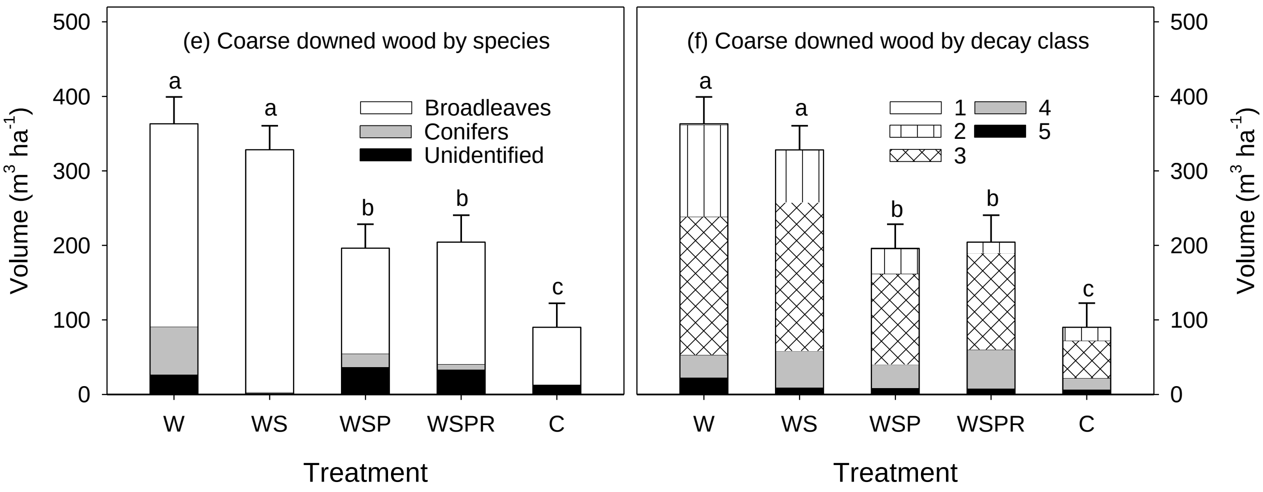
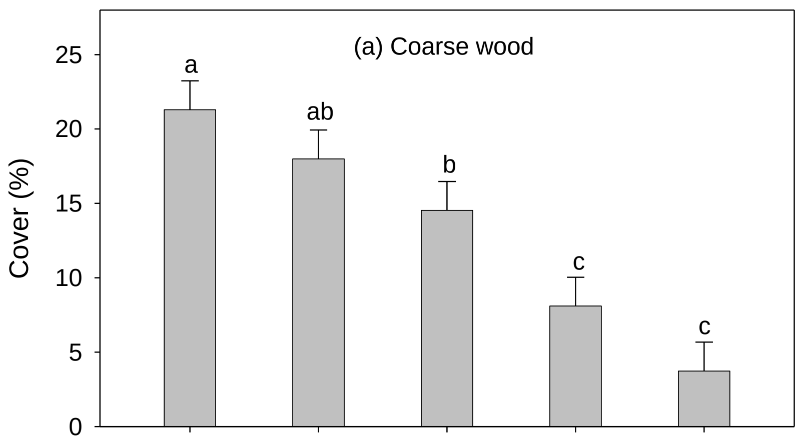


Figure 1. Volume and density of standing live trees (**a**,**b**) and snags (**c**,**d**) by species group, and volume of coarse downed wood by species group and decay class (**e**,**f**) (means ±1 SE) for 5 treatments: Windthrow (W), Windthrow–Salvage (WS), Windthrow–Salvage–Plant (WSP), Windthrow–Salvage–Plant–Release (WSPR), and Clearcut (C). Bars topped by different letters indicate significant differences among treatments ($p < 0.05$).

The volume of standing snags ranged from 4.8 m^3 ha^{-1} in WSPR to 35.3 m^3 ha^{-1} in W (Figure 1c, $p = 0.135$) treatment. Standing snags were mostly trembling aspen (60%) and white birch (20%) and numbers were marginally higher in W (97 pieces ha^{-1}) than in WSPR and C (about 20 pieces ha^{-1}) (Figure 1d, $p = 0.059$) treatments. The difference between treatments W and WS can be attributed to conifer removal during salvage harvesting operations.

3.2. Downed Wood

The volume of coarse downed wood was higher in W and WS treatments than in areas with renewal operations (WSP and WSPR) and the clearcut (Figure 1e, $p < 0.001$). The most frequent decay class of the coarse downed wood was 3, with few in class 1 or 5 (Figure 1f). The proportion of ground area covered by coarse downed wood showed a similar pattern, but was reduced by herbicide release in WSPR treatment relative to WSP (Figure 2a, $p < 0.001$).



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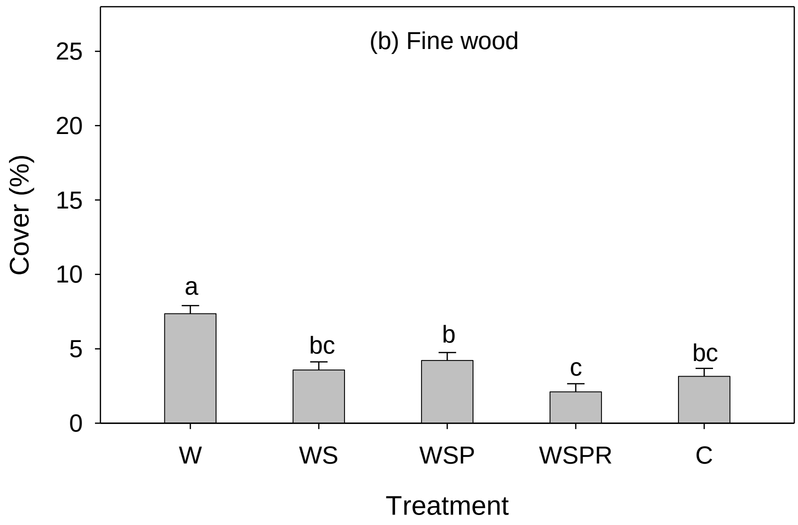
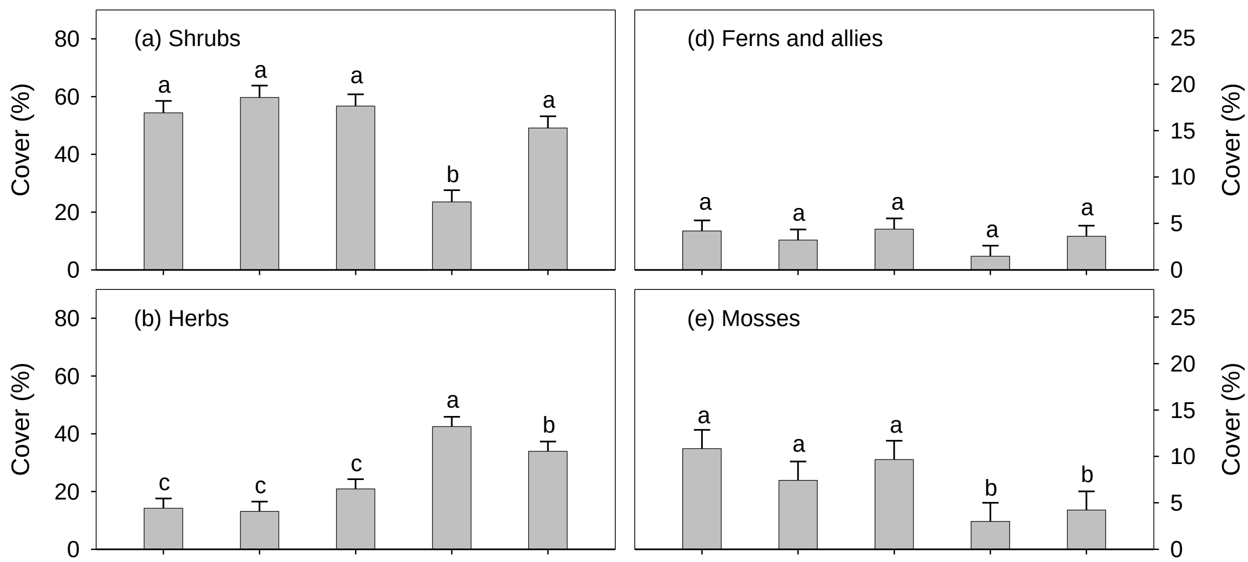


Figure 2. Proportion of ground area covered by coarse (**a**) and fine (**b**) downed wood (means ±1 SE) for 5 treatments: Windthrow (W), Windthrow–Salvage (WS), Windthrow–Salvage–Plant (WSP), Windthrow–Salvage–Plant–Release (WSPR), and Clearcut (C). Bars topped by different letters indicate significant differences among treatments ($p < 0.05$).

Comparatively, the area covered by downed fine wood differed significantly among the five treatments (Figure 2b, $p < 0.001$). All salvage harvesting and renewal operations reduced fine wood, with the lowest cover in the WSPR treatment.

3.3. Vegetation Cover

Shrub cover was lower ($p < 0.001$) and grass and sedge cover was higher ($p = 0.031$) in WSPR than in the other 4 treatments, which did not differ significantly from one another (Figure 3a,c). The total cover of herbaceous species was highest in the WSPR treatment, followed in decreasing order by C, WSP, W, and WS treatments (Figure 3b, $p < 0.001$). Moss cover was lower in WSPR and C treatments (Figure 3e, $p < 0.001$), whereas lichen cover was higher in W than in the other treatments (Figure 3f, $p = 0.005$). Fern and allies cover did not differ among treatments (Figure 3d, $p = 0.410$).



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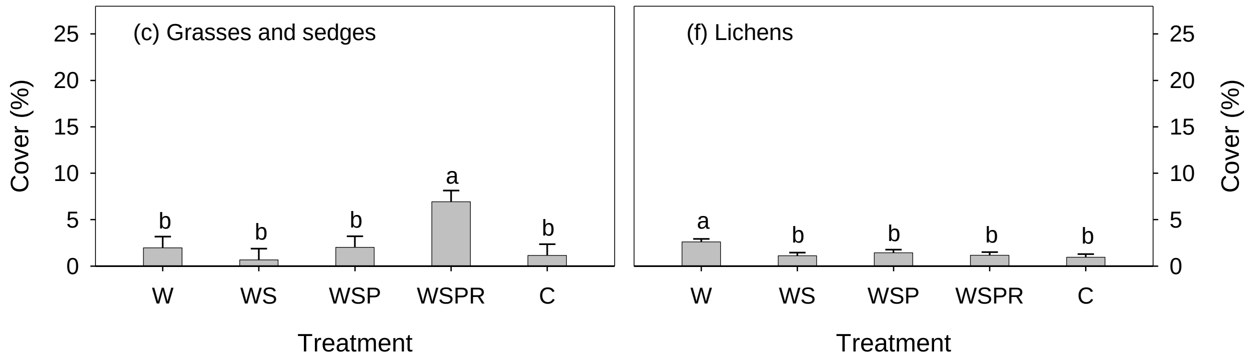
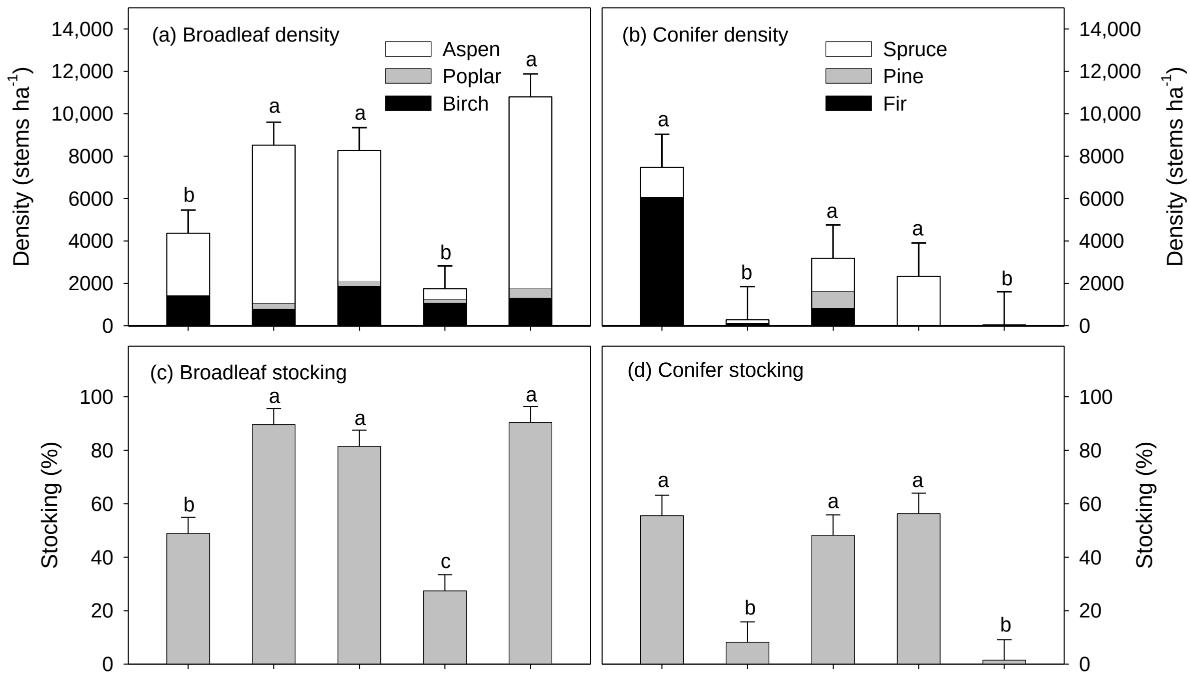


Figure 3. Percent cover of vegetation (means ±1 SE) layers—shrubs (**a**), herbs (**b**), grasses and sedges (**c**), ferns and allies (**d**), mosses (**e**), and lichens (**f**)—for 5 treatments: Windthrow (W), Windthrow–Salvage (WS), Windthrow–Salvage–Plant (WSP), Windthrow–Salvage–Plant–Release (WSPR), and Clearcut (C). Bars topped by different letters indicate significant differences among treatments ($p < 0.05$).

3.4. Tree Regeneration

Among the four post-windthrow treatments, broadleaf regeneration density and stocking were higher in WS and WSP than in W and WSPR, while broadleaf regeneration height and diameter did not differ between W and WSP (Figure 4a,c,e,g, $p < 0.001$). The C treatment had the highest broadleaf tree density, stocking, height, and diameter, but the difference with WS was significant only for total height (Figure 4e). Most broadleaf regeneration was trembling aspen, except in treatment WSPR where glyphosate killed the aspen and left less susceptible white birch (Figure 4a).



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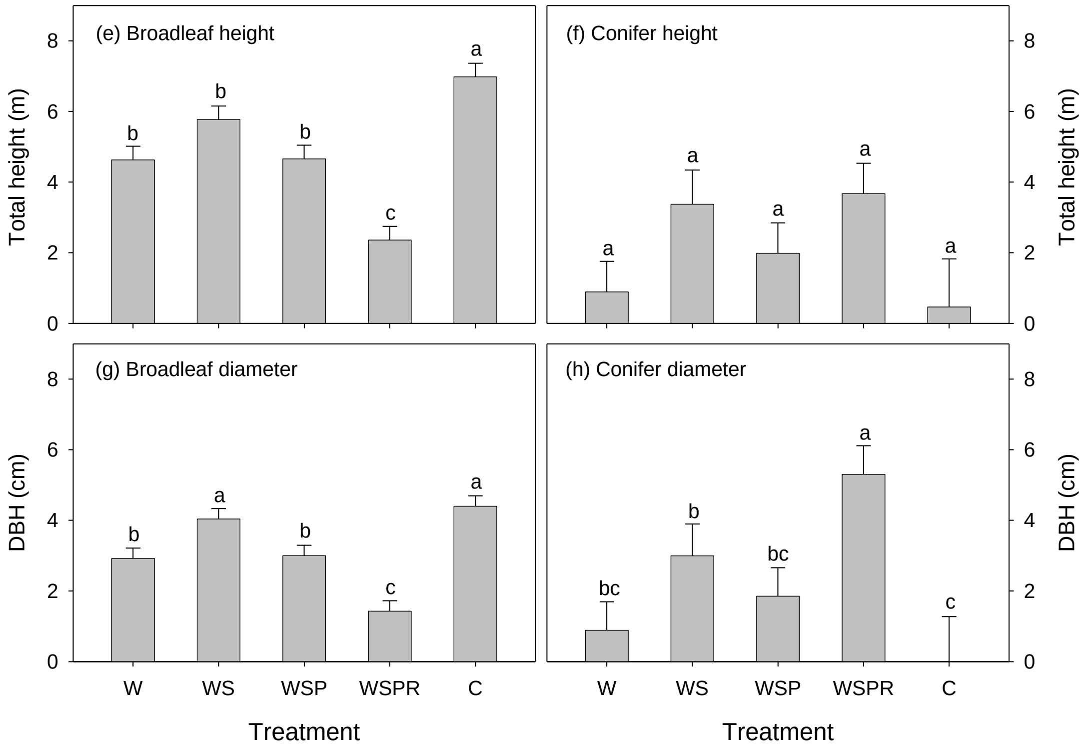

Figure 4. Regeneration density by species (**a**,**b**), regeneration stocking (**c**,**d**), regeneration height (**e**,**f**), and regeneration diameter (**g**,**h**) for broadleaves (left column) and conifers (right column) (means ±1 SE) for 5 treatments: Windthrow (W), Windthrow–Salvage (WS), Windthrow–Salvage–Plant (WSP), Windthrow–Salvage–Plant–Release (WSPR), and Clearcut (C). Bars topped by different letters indicate significant differences among treatments ($p < 0.05$).

Conifer regeneration density and stocking were highest in the W treatment, followed by WSP or WSPR (Figure 4b,d; $p < 0.001$). Regeneration in WS and C was negligible. Among the regenerating conifers, WSPR was almost solely spruce (99%); WSP was mixed spruce (49%), pine (24%), and fir (27%); and W was mostly fir (81%) with some spruce (19%). The regenerating conifers in the WSPR treatment were 3.7 m in height and 5.3 cm in diameter, with the latter significantly larger than that in the other treatments (Figure 4h, $p = 0.005$).

4. Discussion

4.1. Post-Disturbance Dynamics

As with wind disturbances in other forests [9,34], the 2006 windthrow removed much of the aspen stand overstory, creating large quantities of snags and downed dead wood. The year 15 post-disturbance assessment showed an apparent recovery, with overstory volume in W nearly doubled and density nearly quadrupled compared to earlier assessments [7]. The overstory change in W can be attributed to the release of understory balsam fir and spruce [7,8]. Due to the ingress of released understory trees and dieback of old residual trees [27,35] from wind and decadence [36], the average size of overstory trees decreased for both height and diameter.

At the same time, the volume of standing snags in the W treatment decreased by >40% and density by >50%. The larger reduction in density suggests a greater loss of small-diameter snags over time [6,37], due to higher rates of decay [38] and susceptibility to physical movement by wind or wildlife. Average snag diameter increased from 24.5 cm shortly after disturbance to 25.8 cm at year 15. In the W treatment, the decrease in standing snags at year 15 resulted in additional inputs to coarse downed wood volume and percent cover, which remained similar to those observed shortly after disturbance [7].

Comparatively, the cover of fine downed wood decreased substantially, likely due to lack of input from live trees and higher rates of decay for small downed wood [38].

Despite the residual overstory, snags, and downed wood that could interfere with the abundance and growth of the aspen suckers [13], windthrow stimulated aspen vegetative regeneration, consistent with suggestions that windthrow events benefit the regeneration of pioneer species [39–41]. Meanwhile, the windthrown conifers create pits and mounds with a gradient of soil and microclimates [11,12], conditions that encourage the germination and natural regeneration of balsam fir and spruce [7]. Compared to broadleaf regeneration density, which decreased through self-thinning over time [42], conifer density increased in the W treatment, due to natural recruitment of shade tolerant balsam fir in both overstory and understory [7].

4.2. Salvage Logging

Consistent with Waldron et al. [4] and Taylor et al. [9], salvage harvesting operations reduced the abundance of overstory trees, snags, and downed wood at year 15 post-disturbance. Yet, over time, the effects of salvage harvesting weakened and generally became insignificant, likely due to the low harvesting intensity (30%) relative to typical operational levels [24]. The level of salvage would have been higher if market demand for aspen wood had been stronger [7].

The 15-year post-windthrow assessment continues to support the use of operational salvage harvesting for aspen regeneration in terms of resulting density, stocking, and growth, as expected given aspen regeneration biology [13]. These results are consistent with those after prompt post-fire salvage operations in aspen stands [14,15] but differ from those after delayed salvage harvesting [16]. Salvage operations that immediately follow windthrow allow the benefits of the salvage removal to exceed the mechanical damage to aspen regeneration; a delay shifts the benefit–damage balance. Additionally, it was observed in this study [7] and others [22,23] that the salvage operation could damage advanced regeneration of shade tolerant species, such as spruce and balsam fir, although logging operations also add seedbeds for natural regeneration of these species [20–22]. As a result, salvage harvesting may not change total regeneration density and stocking [24] but may increase the proportion of early successional species, i.e., trembling aspen, jack pine, and white birch [9,20,34,43].

Other than a trend of lower lichen cover, salvage harvesting had minimal effects on vegetation abundance [7,44], probably due to the relatively low harvest removal [7], the limited forest floor disturbance by the winter operation [45], and a quick increase in broadleaf regeneration and shrub cover throughout the treatment areas [7]. The lower lichen cover in salvage logged areas [46,47] is probably due to lichen sensitivity to light and moisture conditions and slow recovery following disturbances [35,42,48].

4.3. Forest Renewal Operations

To ensure adequate spruce or pine composition in post-disturbance stands, forest renewal operations are required to increase the density and stocking of the desired crops [49,50]. As per early observations, windrowing coarse wood and planting conifers did not significantly affect the remaining overstory and broadleaf regeneration [7]. However, the windrow site preparation knocked down standing snags and reduced the land area covered by coarse downed wood. Additionally, the windrowing process moved cones across the site, exposed forest floor for seedbeds, and increased light and temperature, all helping the germination of natural jack pine, spruce, and balsam fir [51]. The planted and naturally regenerated trees were adequate in density and stocking, but substantially smaller in diameter than what would be in the Windthrow–Salvage–Plant–Release treatment, which benefits from both planting and vegetation control [49,50].

The reduction in coarse downed wood volume at year 15 in windrowed treatments WSP and WSPR relative to WS is unexpected and differs from early observations [7]. The change is likely due to further decomposition and compaction of coarse wood windrows, adding to the difficulty in identifying pieces underneath wood piles and leading to possible underestimation.

The herbicide release with glyphosate substantially reduced tall vegetation (i.e., overstory, understory broadleaves, and shrubs) and increased the cover of lower vegetation (i.e., herbs and grasses) that responds quickly to disturbance [52,53]. White birch is less responsive to foliar spraying with glyphosate than trembling aspen [54] and it became the dominant broadleaf regeneration in the WSPR treatment. Even so, white birch growth was substantially reduced relative to trees in non-sprayed treatments [49] and not adequate to overtop the conifers. The year 15 assessment confirmed early results from this study [7] and other studies [49,50,55] that reducing tall vegetation benefits the survival and growth of natural and planted conifers.

4.4. Management Considerations and Conclusions

The early effects of windthrow, salvage, windrow site preparation, planting, and herbicide release on overstory trees, standing and down coarse wood, vegetation cover, and regeneration persisted 15 years post-disturbance. The catastrophic windthrow removed much of the overstory, releasing sub-canopy and understory trees and creating large amounts of standing and down coarse wood. Relative to the C treatment, aspen regeneration on other treatment sites was impeded by the coarse wood; however, the abundance and growth of the aspen regeneration in the W, WS, and WSP treatments will be adequate for aspen dominance in future forests. The windthrow event will accelerate the transition of aspen stands ($\geq$80%) to aspen-dominated mixedwoods (50%–80%), similar to the dynamics of aspen stands after defoliation by forest tent caterpillar and the resulting decline [56].

The salvage harvesting only treatment (i.e., WS) removed some of the residual trees and snags, which helped aspen regeneration in terms of density, stocking, and vegetative growth. However, the harvesting operation reduced advanced growth of spruce and balsam fir. If the forest management objective is to restore wind-affected stands to pre-disturbance conditions, a salvage harvest shortly after windthrow is a viable option, and may also benefit the natural regeneration of jack pine and spruce. With the salvage harvesting prescription, the year 15 overstory and understory composition suggests a future forest of pure aspen.

The use of planting and release (i.e., treatments WSP and WSPR) are common practices for increasing conifers in aspen stands after clearcut. The WSP treatment increased conifer abundance but growth of planted spruce was lower than that in the WSPR treatment, due to competition from abundant aspen regeneration and shrubs. The WSP treatment indicates future stands of aspen-dominated mixedwoods similar to those in the untreated windthrow area. If the management objective is a conifer-dominant stand, a post-planting release treatment is needed, as is common practice in Canadian boreal forests following a clearcut [27,35,49,50].

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