Riparian plant composition, abundance, and structure responses to different harvesting approaches in riparian management zones nine years after treatment in Northern Minnesota, U.S.A.

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ABSTRACT

I compared riparian plant responses to different harvesting approaches over nine years in Riparian Management Zones (RMZ) in Northern Minnesota. In Chapter 1, I found that tree regeneration in RMZs is greater in partially harvested treatments (60% BA removal) than in unharvested treatments. This was especially true of intolerant tree species, although the shade tolerant species are becoming important in lower strata at year nine post-treatment. In Chapter 2, I found that understory plant community composition and abundance change somewhat over time in partially harvested treatments in comparison to unharvested treatments. This was especially true of woody understory layers, however, less so for the herbaceous layer. In general, the understory plant community shifted toward more shade intolerant and disturbance indicating species. As of nine years post-treatment, partially harvested RMZs balance timber and non-timber management objectives as they increase tree regeneration and do not dramatically alter understory plant communities.

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CHAPTER ONE:

Effects of residual overstory and harvest methods on regeneration dynamics within riparian management zones in Northern Minnesota, USA.

INTRODUCTION

Riparian areas are ecotones where the functions of upland terrestrial and aquatic ecosystems interact. Riparian areas provide an array of goods and services such as high plant diversity, wildlife habitat, nutrient and sediment storage and flow, timber resources, and recreational opportunities such as hunting and fishing (Gregory et al. 1991; Gilliam 1994). Because these roles and functions are important, it is imperative that we manage riparian areas cautiously (Verry and Dolloff 2000).

Previous research has shown that clearcutting in riparian areas alters the aquatic and terrestrial components of riparian ecosystems (Davies and Nelson 1994; Jewett et al. 1995; Stone and Wallace 1998; Keim and Schoenholtz 1999; Schilling et al. 1999; Jackson et al. 2001; Boothroyd et al. 2004; Governo et al. 2004; Rykken et al. 2007). Because these changes can negatively impact riparian function, riparian buffers where no harvesting is conducted between a water body and managed forest (Grizzel and Wolff 1998; Palik et al. 2000; Blinn and Kilgore 2001) are increasingly used to protect water resources from the effects of forest management. Studies indicate that uncut buffers ameliorate impacts of timber harvesting on abiotic and biotic variables, especially those of streams (Boothroyd et al. 2004; Davies and Nelson 1994; Brosofske et al. 1997; Kinley and Newhouse 1997; Jackson et al. 2001; Governo et al. 2004). Although successful in providing stream protection, uncut buffer strips impede the restoration of and management for diverse riparian areas on the landscape (Palik et al. 2000; Verry and

Dolloff 2000), necessitate foregoing active timber management opportunities (Palik et al 2000; Verry and Dolloff 2000; Zorbrist and Lippke 2007), and prevent financial gain from timber sales (Lippke and Barr 1999; LeDoux 2006; Zorbrist and Lippke 2007).

Designing riparian forest management practices that better balance both ecological and economic values is therefore a high priority. In the last decade, many states have developed best management practices that guide forest managers on the use of riparian management zones (RMZ), buffer strips, and stream protection zones (Gregory 1997; Young 2000; Blinn and Kilgore 2001). In Minnesota, voluntary forest management guidelines make recommendations on buffer widths, equipment use, and residual basal areas in riparian management zones of streams, lakes, and open-water wetlands that also take into consideration water quality, and cultural and recreational resources (Minnesota Forest Resources Council 2005).

Studies evaluating the effectiveness of riparian management have generally concentrated on water resources, water quality, and changes within the aquatic community. These studies suggest that active management in riparian areas (i.e., partial timber harvesting that retains residual vegetation after harvest) can lessen harvesting effects on stream conditions (Boothroyd et al. 2004) and provide adequate protection of water quality (Keim and Schoenholtz 1999; Sheridan et al. 1999; Jackson et al. 2001; Kreutzweiser and Capell 2001; Ruel et al. 2001; Vowell 2001; Governo et al. 2004). A few studies have considered long-term effects of timber harvesting on riparian vegetation, but they have either been focused on immediate to short-term (1-3 years post-management) responses (e.g., Palik et al. 2003; Governo et al. 2004) or on differences in vegetation characteristics in managed and unmanaged riparian zones during one sampling period only (e.g., Dieterich et al. 2006). From these studies, it appears that tree regeneration abundance is often greater in managed buffers than in no-cut riparian buffers (Palik et al. 2003; Governo et al. 2004). For example, in Minnesota, partially cut RMZs had greater average aspen (*Populus* spp.) sucker densities, aboveground aspen biomass, and sucker height compared to uncut RMZs (Palik et al. 2003). Similarly, Governo et al. (2004) found that the biomass of understory vegetation (both woody and herbaceous combined) was greater in partially harvested Streamside Management Zones than in uncut zones nine and fourteen months post-treatment. It is possible that these studies are capturing beginning trends and that statistically significant differences will develop over time. Because the use of residual trees in riparian buffers is a relatively new concept in forest management in the upper Midwestern Lake States, USA, our understanding of regeneration dynamics of woody vegetation and particularly commercially important tree species in response to partial timber harvest in RMZs over time is still limited and long-term monitoring of managed riparian ecosystems is needed to refine existing guidelines.

To be successful in the long-run, RMZ management must accomplish the dual purpose of maintaining ecological continuity and functioning through partial overstory retention and facilitating tree regeneration establishment and growth. Thus, examining woody regeneration after partial harvest provides insight into successional pathways and growth development of longer-lived trees for continued stream protection as well as production of future timber resources of commercially important tree species in RMZs.

The primary objective of this study was to examine the species composition and abundance of woody regeneration (trees and shrubs) in partially harvested RMZs, expanding results reported in Palik et al. (2003) to nine-years post-harvest. Partially harvested RMZs were cut using two different harvest systems: cut-to-length processing and tree-length harvesting. Specifically, we investigated (1) whether or not commercially important tree species were regenerated sufficiently in the partially harvested RMZs and (2) how longer lived, later-successional species responded to the partial harvest in RMZs. Treatments that created conditions of greater light availability below the forest canopy via overstory removal and/or edge effect were expected to exhibit larger changes of tree and shrub density responses that would occur sooner than in uncut treatments. Hence, we anticipated greater amounts of change in woody regeneration densities in partially harvested treatments, intermediate amounts of change in unharvested RMZs adjacent to an upland clearcut, and smallest amounts of change in full control treatments (i.e., no cut in either the RMZ or the adjacent upland). Further, we hypothesized that the greater basal area removal in partially harvested treatments would favor the regeneration of intolerant tree species such as aspen (*Populus spp = P. tremuloides* Michx., *P. grandidentata* Michx, and *P. balsamifera* L.) and paper birch (*Betula papyrifera* Marsh) more than in control treatments.

METHODS

Study Area

The study area is located in the Laurentian Mixed Forest Province (MN DNR 2003) in southern Itasca County, Minnesota (47° 8' 1.298" N, 93° 37' 37.773" W) on land owned and managed by UPM Blandin Paper Company (Figure 1). These forests are within the Northern Minnesota Drift and Lakes Section and are located in the St. Louis Moraines Subsection. The annual precipitation in this area ranges from 61-69 cm, 40%

of which occurs during the 111 to 131 day growing season (MNDNR 2003). Average winter temperature (December – March) is -10.6° C and average summer temperature (June – September) is 16.7° C (MNDNR 2004). The forest community is a Northern Rich Mesic Hardwood Forest (MHn47), which is characterized by loamy, calcareous soils that are well-drained to somewhat poorly-drained, derived from end moraine, and occurs mostly in isolated patches. Windthrow is an important natural disturbance in these forest types (MNDNR 2003). All experimental units are secondary upland and riparian forests ranging in age from 70-120 years prior to treatment. The dominant tree species before harvest (Appendices A and B) included aspen (13-24% relative basal area (RBA) and 7-10% relative density (RD)), paper birch (10-19% RBA and 13-20% RD), sugar maple (*Acer saccharum* Marsh.; 8-22% RBA and 14-32% RD), and basswood (*Tilia Americana* L.*;* 1-15% RBA and 2-15% RD). Northern white-cedar (*Thuja occidentalis* L.) and black ash (*Fraxinus nigra* Marsh.) become more dominant at the stream edge.

Experimental Design

Twelve experimental units were established in 1997 and centered along four 1st order streams (~1 m in width) that drain into Pokegama Lake (Figure 2). The units had a north-south orientation and were each approximately 4.86 ha in size. A buffer of at least 100 m separated units that were located along the same stream. A RMZ was designated in each unit, which ran the width of the unit. The RMZ was centered on the stream (extending 30.5 m on each side) and its boundary generally extended into the adjacent upland forest. A slight elevational gradient of topographical features (fluvial landforms) extended from the stream to the upland and includes stream floodplains, slopes, and terraces. Landform types and extent were variable among units.

The experiment used a complete randomized design consisting of four treatments that were randomly assigned to each of three replicates. The four treatments include (1) Full Control (with no harvesting in either the RMZ or upland portions of the stand); (2) Riparian Control consisting of an uncut RMZ with an adjacent upland clear cut; and two RMZ partial cut treatments using either (3) traditional tree-length harvesting (TL) and (4) cut-to-length harvesting (CTL). In both partially cut RMZ treatments overstory trees ($\geq$ 10 cm diameter at breast (1.37 m) height (DBH)) were harvested to a residual basal area of 12.4 m^2 ha^{-1} (60 % removal); the adjacent uplands were clearcut and harvested with the same method as their RMZ counterparts. Upland areas adjacent to Riparian Controls were harvested using the CTL method. Harvesting was conducted in the late summer to early fall of 1997. There was a gradient of harvesting intensity in the RMZ portion of the stands, ranging from low intensity removal of overstory trees at the stream to to high intensity at the clearcut edge. No trees were harvested within 5 m of the stream edge. This harvesting design is thought to better protect riparian function as there is a greater probability of terrestrial and aquatic ecosystem interaction exists closer to the body of water (Palik 2000). The original design of this study was established to measure the effectiveness of the earliest version of Minnesota’s Best Management Practices for forested riparian areas (MFRC 1995).

Sampling Design

In each unit, five to eight transects were established perpendicular to the stream (81 transects in total) (Figure 2). Five to eight permanent plots (437 total) were placed in the center of each fluvial landform (i.e. floodplain, slope, terrace) on each transect. One point was generally established in the upland within the RMZ, and one in the upland outside of the RMZ. All vegetation sampling was centered on or emanated from these permanent plots. Each transect crossed the stream and plots were established on both sides of the stream such that at least one to two plots generally occurred on one side (the short side of transect) and four to six plots occurred on the opposite side (long side of transect). Short and long sides of each transect usually alternated on the north and south side of the stream. Because plots were placed in different fluvial landforms, distances between plots varied according to inherent topographic variation. Permanent plot centers were marked with metal stakes in 1997 and, if necessary, re-monumented in the summers of 2005 and 2006 or re-established if not found (30 plots total).

Vegetation Sampling

In each permanent plot, woody vegetation sampling occurred during the summers and included overstory trees (≥10 cm at DBH, or 1.37m above the ground), tree saplings (2.5 – 9.9 cm DBH), the large woody regeneration layer (>1m tall and < 2.5 cm DBH), and the small woody regeneration layer (≤1 m tall). Overstory trees and saplings were sampled in 1997 (pre-harvest) and 2006 (yr 9 post-harvest) using the point-quarter method (following Brower and Zar 1984). Species, DBH, distance from plot center up to a maximum distance of 30 m were recorded for the closest tree in each quadrant. If no tree was encountered within 30 m from the sample point in a particular quadrant, an absent tree (DBH=0) was recorded with a distance of 30 m from the center point. Overstory density and basal area and sapling density per treatment unit were computed for all species combined and by species (see Appendices A-C) following Mitchell (2006). Additionally, to quantify residual basal area and density of the partially harvested treatments, a complete census of the overstory trees was conducted in 1998 (yr 1 post-harvest) in the CTL and TL units; species and DBH were recorded for each residual tree from which overstory density and basal area (1998) were computed for each of these treatment units.

Large woody regeneration was sampled in 1.5 m radius circular plots that were centered on each permanent plot center during the summers of 1997 (pre-harvest), 1998 (1 year post-harvest), 2000 (yr 3 post-harvest), and 2006 (9 years post-harvest). Species and number of stems were recorded for each individual within the plot. Small woody regeneration was sampled during the summers of 1997, 1998, 2000, and 2006 in 0.5 m^2 square plots that were off-set by 1 m from the permanent plot center. The direction of the offset was determined by location of the stream such that plots on the north side of the stream were located 1 m north of plot center and those on the south side of the stream were located 1 m south of plot center. Individuals were identified to species and number of stems was recorded. The density of woody regeneration was summarized by treatment for each time period sampled. Additionally, densities of the tree and true shrub components were computed separately for both layers to better gauge future success of tree regeneration.

Measurements of coarse woody debris (CWD) volume were taken for the 2006 sampling period only. CWD was sampled using line transect sampling in the RMZ portion of every unit. Every permanent plot was assigned a random azimuth using a random number generator. One 5 m transect was run in the direction of the azimuth starting at the permanent plot center. For each piece of CWD with an intersection-diameter of ≥ 10 cm, species, length, decay class, and the intersection-diameter were recorded. If the species of each individual piece could not be confidently determined, it was classified as either hardwood or conifer. CWD volume (m^3 ha^{-1}) was estimated for each treatment unit using the methods per Van Wagner (1968).

Blowdown density accumulation (stems ha^{-1}) over the nine year period was calculated by subtracting the overstory tree density in 2006 from the density in 1998 for each treatment unit. Percent blowdown density accumulation (as a proportion of the overstory density in 1998) was calculated to standardize all treatments. This was necessary because the partial harvested treatments had fewer trees that could potentially fall down than the Full Control and Riparian Control treatments.

Data Analysis

Density of the overstory, sapling layer, and the large and small woody regeneration layers was modeled as a function of time, treatment, and time-by-treatment interaction with repeated measures analysis using a repeated Mixed ANCOVA model (Proc Mixed). Pre-treatment values were added as a covariate in the repeated measures analysis to test whether baseline levels affected the magnitude of change in the response variables. The repeated and random statements for all tests were time and unit nested in treatment, respectively. Several covariance structures appropriate for unequal lengths of time between sampling periods (i.e., one year, three years, and nine years post-treatment) were examined and the structure with the lowest Akaike Information Criterion (AIC) value was chosen for the analysis. Multiple comparisons tests were performed to address questions pertaining to treatment by time interactions, i.e., whether and how (1) woody regeneration density changed over time in each treatment and (2) woody vegetation density was different among treatments in each time period. A Bonferroni correction for the multiple comparisons tests was used to maintain an overall type I error of $\alpha = 0.10$. Thus, most individual hypothesis tests have to be evaluated at corrected α_i levels of 0.0083 ($\alpha_i = 0.10/12$) for time comparisons within treatment levels (question 1) and at 0.005 ($\alpha_i = 0.10/18$) for treatment comparisons within each level of time (question 2). However, some variables had different corrected α_i levels because they were not measured as often as others (they had different levels of time; see Appendix D for multiple comparison explanations). Density was modeled for the overstory, the sapling layer including separate models for aspen and paper birch, the entire large and small regeneration layers, the tree component of both layers including separate models for aspen, paper birch, and sugar maple, and the shrub component of both layers, including separate models for mountain maple (*Acer spicatum* Lam.), hazel (*Corylus* spp. = *C. americana* Walter and *C. cornuta* Marsh.), and raspberry (*Rubus* spp. = *R. idaeus* L. ssp. *strigosus* (Michx) Focke and *R. allegheniensis* Porter) in the large regeneration layer only.

Differences among treatments in CWD volume and blowdown accumulation, for which data were only available for year nine, were assessed with a one-way ANOVA

(Proc GLM). Data were transformed with the natural log as necessary. F-tests were considered significant if $p \leq 0.10$. All analyses were performed using the SAS 9.1 (SAS Institute 2004) software.

RESULTS

Changes in the overstory layer

Average pre-harvest overstory basal areas (BA) and tree densities (TPHA) across all treatment units ranged from 26.3 to 33.7 m^2 ha^{-1} and from 606.0 to 759.3 trees ha^{-1}, respectively, and were not significantly different among treatments (Table 1). Harvesting in the RMZ reduced basal areas and stem densities by 51% and 61% (BA) and by 60% and 56% (TPHA) in the CTL and TL treatments, respectively (Figure 3 and Figure 4, respectively). Between the years of 1998 and 2006, basal areas and stem densities were further reduced by an additional 3% (BA; $p = 0.021$) and 34% (TPHA; $p < 0.001$) in the Riparian Control stands. In the partially harvested stands, basal areas and stem densities were reduced by 51% and 55% (BA) in the TL ($p = 0.037$ <not significant at $\alpha = 0.100$>) and CTL ($p = 0.0285$ <marginally significant>), respectively and 42% and 51% (TPHA) in the TL ($p = 0.031$ <not significant>) and CTL ($p = 0.017$) treatments, respectively. These differences were attributed to blowdown. Concurrently, overstory basal area increased by 0.3% ($p = 0.98$) and density was reduced by 7% ($p = 0.37$) in the Full Controls although these results are not significant. There were significant differences among treatments in the development of basal areas ($F_{6,16} = 16.84$, treatment×time $p < 0.001$) and tree densities ($F_{6,16} = 16.47$, treatment×time $p < 0.001$) over time.

Although average CWD volume (Table 2) in year nine was lower in the Full Controls when compared to the Riparian Controls and two harvested RMZ treatments, the differences were not significant ($F_{3,8} = 2.4$, $p = 0.15$). In contrast, percent blowdown accumulation in year nine was significantly different among treatments ($F_{3,8} = 3.11$; $p = 0.089$). The Full Control treatment had significantly less percent blowdown than the Riparian Control, CTL, and TL combined ($p = 0.0196$). Further, the Riparian Control was not different from the Full Control ($p = 0.090$) or the partially harvested treatments ($p = 0.46$).

Changes in the sapling layer

Prior to harvest, average sapling density ranged from 352.9 to 531.3 stems ha^{-1} (Table 3) and was not significantly different among treatments. Average sapling density differed significantly among treatments at year 9 post harvest ($F_{3,8} = 4.46$; $p = 0.040$) (Figure 5). Sapling density increased significantly in the CTL treatment from their immediate post harvest condition to year nine post harvest, where it roughly doubled in magnitude ($p = 0.006$), whereas the TL density did not increase significantly ($p = 0.057$, $\alpha = 0.025$). At year nine post harvest, the CTL and TL had greater sapling density than the Riparian Control and Full Control treatments (all $p < 0.007$, except for TL yr 9 vs. Control yr 9, which was marginal, $p = 0.029$, $\alpha = 0.021$). Further, the sapling density at year nine in the Riparian Control was significantly lower than the sapling density in the Full Control ($p=0.007$).

The increase in sapling density in the partially harvested treatments was largely due to significant increases of shade intolerant aspen ($F_{3,8} = 9.73$; $p = 0.005$) and paper birch ($F_{3,8} = 6.50$; $p = 0.015$). Immediately post harvest, there were no aspen present in the sapling layers in any treatment unit (Table 3, Figure 6). By year nine, aspen density had increased at least an order of magnitude more in the partially harvested treatments than in the Control and Riparian Control and aspen density in the partially harvested treatments was significantly greater than in the Riparian Control and Control treatments (all $p < 0.002$). Aspen density in the Riparian Controls did not differ significantly from the Full Controls ($p = 0.57$). Similar results were seen for paper birch (Figure 7) in that sapling density significantly increased from year one to nine in the partially harvested treatments only (both $p = 0.01$). The TL treatment had greater paper birch density than the Control ($p = 0.011$) and Riparian Control ($p = 0.018$). The CTL, however, had greater average density, but it was not statistically significant (Control $p = 0.058$ and Riparian Control $p = 0.097$, $\alpha = 0.021$). The more shade tolerant sugar maple (Figure 8) and basswood (Figure 9) showed no significant changes in sapling density over the duration of the study ($F_{3,8} = 0.42$; $p = 0.74$ and $F_{3,8} = 1.67$; $p = 0.25$, respectively).

Changes in the large regeneration layer

Overall density changes over time in the large regeneration layer (both trees and true shrubs combined) were strongly influenced by treatment (treatment×time: $F_{9,24} = 9.29$, $p < 0.001$) (Figure 10). Large regeneration layer densities increased significantly over time in both CTL and TL treatments, but did not change in the Full Control or Riparian Control treatments. Compared to year one, densities in year three were 5.6 times greater ($p < 0.001$) in the CTL and 2.8 times greater ($p < 0.001$) in the TL treatments. Additional increases in large regeneration density were seen by year nine when density was 7 times greater ($p < 0.001$) in the CTL and 4 times greater ($p < 0.001$) in the TL treatments compared to year one. Accordingly, at year 3 post-treatment, the density in the large regeneration layer in year three was approximately 7.2 times greater in the CTL ($p < 0.001$) and 5.7 times greater in the TL ($p < 0.001$) than in the Full Control treatment, and about 4.1 times higher in both the CTL ($p < 0.001$) and 3.2 times greater in the TL ($p = 0.025$) than in the Riparian Control treatment, respectively. By year nine, density in the large regeneration layer was still significantly greater in the partially cut treatments than in the Full Control (both $p < 0.002$) and the CTL compared to the Riparian Control ($p = 0.002$), however, there was no significant difference between the TL and the Riparian Control by year 9 ($p = 0.0064$).

The development over time of the density of tree species in the large regeneration layer (true shrubs were excluded) was significantly different among treatments (treatment×time $F_{9,24} = 6.39$, $p < 0.001$), particularly between partially cut and uncut RMZs (Figure 11). Tree density in the CTL treatment increased by a factor of 6 from year one to year three ($p < 0.001$) and declined between years three and nine (not significantly, $p = 0.075$) such that tree density was still 4.5 times greater in year nine than in year one ($p < 0.001$). Similarly, tree density in the TL treatment increased by a factor of 2.8 from year one to year three ($p < 0.001$) and showed a similar pattern of decline from years 3 to 9 post-treatment (not significant, $p = 0.046$), with the density in year 9 being 1.8 times greater than the year 1, although not significant ($p = 0.033$). In contrast, tree densities in both the Full Controls and Riparian Controls remained largely unchanged over time. Significant differences in tree densities among treatments existed in year three, but did not persist through year nine after harvest with the exception of greater tree density in the CTL compared to the Control ($p < 0.001$). At year 3, tree densities in the CTL and TL treatments were both about 6.6 times greater than in the Full Controls and about 4 times greater than in the Riparian Controls, respectively (all $p < 0.002$).

Aspen density changes over time strongly depended on the treatment (treatment×time $F_{9,.24} = 10.64$, $p < 0.0001$) (Figure 12). Aspen density increased by a factor of 9 in the CTL ($p = 0.002$) between year one and year three. In the TL, aspen density increased by a factor of 2.6 treatment from year one to year three but this result is only marginally significant ($p = 0.007$). Between year three and year nine aspen density decreased significantly by a factor of 6 in both the CTL and TL treatments (CTL $p < 0.004$; TL $p < 0.001$). In year three, aspen densities were over two orders of magnitude greater in the partially harvested treatments than in the Riparian Controls (CTL $p = 0.068$ and TL $p = 0.016$ [both not significant]) and Full Controls (CTL $p = 0.095$ [not significant] and TL $p = 0.024$) but most of these differences are not significant.

Changes of paper birch density in the large regeneration layer through time in each treatment were significantly different (treatment×time: $F_{9,24} = 2.54$, $p = 0.033$). The density of paper birch increased greatly in the partially harvested treatments (Figure 13). From year one to nine, the densities of paper birch increased by a factor of 17 ($p < 0.001$) in the CTL treatment. Similarly, paper birch, which was virtually absent in year one in the TL treatment, increased to 450 ± 153 stems ha^{-1} ($p < 0.003$) in year nine. In year three, the average paper birch densities in the Full Controls and Riparian Controls were less than 1 ± 110 and 67 ± 144 stems ha^{-1}, respectively and were at least 7 times less than the paper birch densities in both partially harvested treatments but these differences were not significant (all $p > 0.01$, $\alpha = 0.006$). The average density of paper birch varied in year nine and was similar for the Riparian Control and partially harvested treatments (all $p > 0.108$). Although, differences in densities widened in year nine for the Control Treatment compared to the partially harvested treatments, significant differences were detected between Control and CTL only ($p = .0028$; TL $p = 0.057$). Furthermore, the Riparian Control had 22 times greater paper birch density at year nine compared to the Control but this difference was not significant ($p = 0.109$).

Changes in sugar maple density also depended on the treatment (treatment×time: $F_{9,24} = 3.78$, $p = 0.004$) (Figure 14). Sugar maple densities increased from 577 ± 690 stems ha^{-1} (year one) to 3967 ± 1075 stems ha^{-1} (year nine) in the CTL treatment ($p = 0.001$) and from 879 ± 690 stems ha^{-1} to 4387 ± 1075 stems ha^{-1} in the TL treatment ($p < 0.001$). Further, differences in sugar maple density were marginally greater and significantly greater in year nine than in year three in the CTL ($p = 0.0089$, $\alpha = 0.0083$) and TL ($p = 0.005$), respectively. In comparison, there were no significant differences in density among the Riparian Control and Control Treatments compared to the partially harvested treatments in any post year time period (all $p > 0.022$, $\alpha = 0.0083$). Lastly, although in year nine, the Riparian Control treatment had 3 times greater sugar maple density than it did in year one, this increase is not significant ($p = 0.464$).

Stem density of woody shrub species in the large regeneration layer changed differentially among treatments over time (treatment×time: $F_{9,24} = 5.73$, $p < 0.001$) (Figure 15). Shrub density increased consistently through time in both partially harvested treatments, where it was 13 times greater in year nine compared to year one (both $p < 0.001$). Changes in shrub density through time were not statistically significant in the

Full Control and Riparian Control treatments. Consequently, shrub densities in year nine were 19 times lower ($p < 0.001$) in the Full Controls and 3.4 times lower ($p < 0.003$) in the Riparian Controls than in the partially harvested treatments.

Mountain maple (treatment×time: $F_{9,24} = 5.31$, $p < 0.001$), hazel (treatment×time: $F_{9,24} = 2.64$, $p = 0.028$), and raspberry (treatment×time: $F_{9,24} = 4.11$, $p = 0.003$) were largely responsible for the increase in shrub species in the large regeneration layer. Average mountain maple density (Figure 16) remained relatively constant in the Full Controls (54 ± 387 stems ha^{-1}) and Riparian Controls (408 ± 387 stems ha^{-1}) over time, but increased by a factor of 8.6 in the CTL ($p < 0.001$) and a factor of 7 in the TL ($p < 0.001$) from year one to nine. In year nine, mountain maple density was 42 times greater ($p = 0.001$) in the CTL and 36 times greater ($p = 0.004$) in the TL treatment than in the Full Control treatment. Although mountain maple density was 3.2 and 3.7 times greater in the CTL and TL, respectively, than the Riparian Control treatment in year nine, these differences were not significant at the $\alpha = 0.0083$ level. Hazel density (Figure 17) increases between year one to year nine were significant only in the CTL treatment ($p < 0.001$); hazel density was 12 times greater in year nine than year one. Raspberry (Figure 18) was virtually absent in the large regeneration layer in all treatments in years one and three but in year nine, the CTL and TL treatments had significantly greater raspberry density ($p = 0.002$ and $p < 0.001$, respectively) . In year nine, however, large differences in raspberry density were present between the controls and partially harvested treatments. Raspberry density was significantly higher in the TL treatments than in the both the Riparian Control and Full Control treatment at year nine (both $p < 0.001$) whereas the CTL treatment had marginally greater raspberry density than the Full Control at year nine

($p = 0.007$, $\alpha = 0.0056$). Although raspberry density was 3.0 times greater in the CTL compared to the Riparian Control treatment in year nine, these differences were not significant at the $\alpha = 0.005$ level. Lastly, the TL treatment had approximately twice the average density of raspberry as compared to the CTL treatment at year nine, but this is not significant ($p = 0.029$).

Lastly, there were significant differences between the densities of shrub species and tree species by treatment in year nine (treatment×plant form: $F_{3,16} = 6.26$, $p = 0.005$). Only the Full Control treatments had significantly greater tree than shrub densities in the large regeneration layer ($p < 0.001$); no significant differences between shrub and tree densities were detected in either the Riparian Control, CTL, or TL treatments in year nine.

Changes in the small regeneration layer

Unlike in the large regeneration layer, overall density in the small regeneration layer did not change over time in the different treatments (treatment×time $F_{9,24} = 0.61$, $p = 0.777$) (Figure 19). Tree density (species that are considered commercial trees) in the small regeneration layer did not change over time in the different treatments either (treatment×time $F_{9,24} = 1.38$, $p = 0.249$) (Figure 20). The only tree species that notably changed over time in the different treatments was aspen (treatment×time $F_{9,24} = 36.90$, $p < 0.001$) (Figure 21). Aspen density increased substantially in response to harvest, but decreased significantly between years one and three (by a factor of 38 (CTL) and 24 (TL), both $p < 0.001$). Aspen density, which had also increased in the Riparian Control after harvest, decreased to a quarter of the post-harvest density between years one and three ($p = 0.001$). In year one, aspen density was 9.0, 16.0, and 4.5 times less in the Full Control than in the CTL, TL, and Riparian Control treatments, respectively ($p < 0.001$ for all), and aspen density was 2.0 and 3.5 times greater in the CTL and TL treatments than in the Riparian Controls, respectively ($p < 0.001$ for both). Further, aspen density was 1.8 times lower in the CTL than the TL treatment in year one ($p < 0.001$), but no significant differences were observed in aspen density among the treatments in years three and nine.

Lastly, the density of shrub species in the small regeneration layer did significantly change over time among treatments (treatment×time $F_{9,24} = 4.12$, $p < 0.003$) although no significant differences were detected in pairwise comparisons (Figure 22).

DISCUSSION

Tree regeneration response to treatments over time

The primary objective of this study was to compare the species composition and abundance of tree regeneration over a period of nine years post-treatment. My results indicate that the overall density and species composition of post-harvest regeneration was not different between the two types of harvesting systems employed (i.e., cut-to-length and tree-length), extending similar 3-year post-harvest findings by Palik et al. (2003) to nine years post-harvest. Moreover, I had originally hypothesized that the Riparian Control would be intermediate between the partially harvested and the Full Control treatments. The Riparian Control was generally intermediate; however, it was most similar to the Full Control in that changes in both control types were minimal for most variables throughout the length of our study. Nonetheless, when contrasting vegetation changes between the two partially harvested and the two control treatments, I found significant differences for most response variables at some time periods after harvest. At what time period these differences were most pronounced between harvested and unharvested treatments depended on the response variable. Finally, my results have to be interpreted in light of unplanned, additional reductions in overstory tree density due to blowdown.

Overstory removal from harvesting and blowdown

Harvesting reduced the average overstory basal areas in the partially harvested treatments by 60%. Between years one and nine after harvest, blowdown further reduced overstory densities between 30-50% in the RMZs that were adjacent to upland clearcuts; blowdown accumulation was much less in Full Controls. Although our estimate of blowdown accumulation measured the combination of blowdown (directly or indirectly via mortality from a falling tree) and dead standing trees, the reduction of overstory can be mostly attributed to blowdown (M. Martin, personal observation). In addition, similar median CWD volumes found in the Riparian Control and partially harvested treatments (Table 2) indicate that much of this is attributable to blowdown in the Riparian Controls. Similar results were reported in a study addressing CWD in riparian zones located in eastern Kentucky (McClure et al. 2004). The authors showed that 18 years post harvest, there were no differences in CWD volume and biomass between harvested and unharvested riparian zones (with a 15 m buffer). Further, the unharvested buffer treatment had significantly greater CWD than their control treatment. They concluded that windthrow and/or slumping was greater in the unharvested buffer and was the likely cause of the difference in CWD between their control and unharvested buffer treatment. As of nine years post-harvest, the results of this study show that there was no difference in CWD volume between harvested and unharvested RMZs. Although not significant, these treatments had greater CWD volume than the Full Control treatment (Table 2). The clearcut edge is likely a reason for this, although the lack of significance is attributed to high variation.

Many studies have shown that mortality from windthrow can be substantial in riparian buffer zones (Steinblums et al. 1984; Grizzel and Wolff 1998; Liquori 2006; Martin and Grotefendt 2007). Windthrow is generally viewed as causing riparian buffers to fail at protecting aquatic habitat and is considered an economic loss in terms of timber (Steinblums et al. 1984; Grizzel and Wolff 1998). However, additions of large wood into stream systems from windthrow can enhance stream functions (Grizzels and Wolff 1998). Additionally, windthrow can also create opportunities for woody tree regeneration or subcanopy tree growth via gap formation (Oliver and Stephens 1977; Webb 1989; Dyer and Baird 1997). Generally, large canopy disturbances favor a new cohort of seedlings whereas a small canopy disturbance is more likely to be filled in with existing subcanopy trees (Oliver and Stephens 1997).

In this study, there was far greater understory regeneration in the partially harvested RMZ treatments than in the Full and Riparian Control treatments. Further, the CTL and TL treatments had less overstory residual basal area than the Riparian Control and therefore may have had more and possibly larger canopy openings, which could explain why there was more woody regeneration in the harvested treatments. Although the Riparian Controls lost 30% of their pre-treatment density, it is possible that overstory basal area was not sufficiently reduced to increase woody regeneration in that treatment. Other studies have found similar results in that overstory retention thresholds must be crossed for the understory community to change (Deal 2001; Zenner et al. 2006; Macdonald and Fenniak 2007). Therefore, it is likely that the threshold was crossed in the partially harvested treatments but not in the Riparian Control treatment. It is unknown whether further blowdown will occur to increase gaps in the future as it is thought that the susceptibility of trees to windthrow diminishes after the first few years following harvest (Steinblums et al. 1984). Nonetheless, the removal of overstory trees in the partially harvested RMZ treatments from harvesting in addition to the further loss of overstory trees attributed to blowdown has likely created sufficient canopy gaps for woody understory establishment and further advancement.

Treatment Comparisons: Cut-to-length vs Tree-length

There was little difference between the CTL and TL treatments and the Control and Riparian Control treatments in terms of tree regeneration. Although the TL harvesting system did disturb and expose more soil than the CTL (Mattson and Thompson 1998), which can alter woody plant density, we did not detect much difference in response between the two treatments. A significantly greater aspen density in the small regeneration layer at year-one post-harvest and two times greater raspberry density at year nine post-harvest in the TL in comparison to the CTL treatment were two notable exceptions. However, the difference in aspen density between these two treatments did not carry on through time in successive vegetation layers. Although traditional tree-length harvesting is thought to be better at regenerating aspen than other methods as it better scarifies soil and kills competing vegetation (Perala 1977), aspen recruitment into upper forest strata is also strongly influenced by light availability (Perala 1990). In this study, both partially harvested treatments had similar average overstory basal areas throughout the study period and similar aspen regeneration densities.

Stem density in small and large regeneration and sapling layers dramatically changed in both the CTL and TL treatments from one to nine years post-harvest. A progression of regeneration was observed among the regeneration layers over time. In the small regeneration layer, average density decreased by year three. This decrease seems to correspond to the increase in the average density in the large regeneration layer at year three. Further, by year nine, average density of saplings had increased. This progression of smaller stems moving up into taller vegetation strata was also observed for tree species in the small and large regeneration layers, notably for intolerant aspen and paper birch that advanced to successively taller strata. It should be noted, however, that the adjacent upland clearcuts had far greater woody regeneration than the partially harvested RMZs. For example, there was a 1.7 times greater aspen density in the large regeneration layer at year three and 6.6 times greater aspen density in the sapling layer at year nine post-treatment in the upland clearcuts than in the partially harvested RMZ treatments (differences not statistically analyzed). Also, there was a clear pattern of decreasing aspen density in each successive vegetation layer that can be attributed to density dependent mortality (Perala 1990).

Average density of the tolerant tree species such as sugar maple significantly increased in the large regeneration layer over time in the partially harvested treatments. However, sugar maple density was not significantly changed in the sapling layer.

Consequently, this species did not exhibit the same progression in density into successive forest strata as the intolerant tree species. The intolerant tree species appear to be advancing more quickly through forest strata than tolerant tree species in partially harvested treatments, which agrees with findings reported by Perala (1977).

Treatment Comparisons: Riparian Control

One of the most surprising findings is that even with likely edge effects from the adjacent upland clearcut and the 30% blowdown accumulation in the Riparian Control, a significant regeneration response was not seen in this treatment. It is known that microclimatic edge effects extend into interior forest (Chen et al. 1995; Heithecker and Halpern 2007) and that woody vegetation often responds with greater abundances at edges (Fraver 1994; Gignac and Dale 2007). For example, Dieterich et al. (2006) found that uncut riparian areas adjacent to managed uplands contained twice the woody stem density (stems greater than 0.5 m tall and less than 5 cm dbh) than in unmanaged reserve riparian forests 23 years after harvest in watersheds in the Adirondack Uplands of New York. In contrast, our Riparian Control treatments did not have significant increases in woody regeneration. However, this study’s buffers are 1.5 times wider than those in Dieterich et al (2006) and could contribute to the difference in our results as narrower buffers have greater light levels than wider buffers (Brosofske et al. 1997).

Vegetation dynamics in the Riparian Control were more similar to the Full Controls than the partially harvested treatments. The creation of an edge from adjacent upland clearcuts has been shown to increase light in riparian areas (Dignan and Bren 2003). Additionally, blowdown, probably caused in part by the creation of edge between partially cut and uncut areas (Liquori 2006; Lopez et al. 2006) likely increased light availability even further. It was thought that the edge effect from the boundary of the clearcut and uncut RMZ would cause an increase in tree regeneration in the Riparian Control treatment. Despite blowdown and edge, the data showed no significant difference in tree regeneration abundance or species composition over time in the Riparian Controls; significant change was only seen in the partially harvested treatments. The difference in tree regeneration of partially cut and uncut RMZs was likely a function of overstory reduction and the associated environmental changes it brought about (i.e. additional light availability, greater soil temperature fluctuations, greater bare mineral soil exposure, etc.). As of nine years post-harvest, any increase in light availability from the clearcut edge and overstory reduction due to blowdown accumulation in the Riparian Control treatments was not sufficient to stimulate and increase tree regeneration in these treatments. Although this was surprising, it likely explains why the Riparian Controls were most similar to the Full Control treatment.

Another factor that could influence changes in tree regeneration differently in the partially harvested RMZs compared to the Riparian Control treatments was the disturbance via tree harvest itself. It is well known that aspen, which was largely responsible for the increase in tree regeneration in this study, suckers profusely after parent stems are cut and that sucker density is a function of amount of aspen stem density removal (Perala 1990). Because aspen stems were not cut in the RMZ portion of the Riparian Control treatment, much lower densities of aspen regeneration in that treatment as compared to the partially harvested treatments should be expected. Although light availability is important for regeneration as well, it is needed more for the continued growth of aspen suckers (Perala 1990) and the development of later-successional species, like sugar maple (McClure et al. 2000; Cole and Lorimer 2005), which did advance to the large regeneration layer in year nine post-treatment in the partially harvested treatments.

Shrub species response to treatment over time

Average densities of shrub species in both the small and large regeneration layers increased from years three to nine post-treatment only in the CTL and TL treatments and was likely a response to the creation of gaps in the canopy (Ehrenfeld 1980) and/or edge (Fraver 1994; Gignac and Dale 2007). Increased abundance of non-tree woody understory is typical after harvest and the response is often proportional to basal area removal in Northern Hardwood forests (Metzger and Schultz 1984; Fredericksen et al 1999). As of year nine, average densities of shrubs and trees in the small regeneration layer were statistically not different from one another, nor were the differences in average densities of shrubs and trees in the large regeneration layer. The Full Control is the only treatment that had higher tree density than shrub density in both small and regeneration layers. Further, the Riparian Controls also had higher tree density than shrub density in the small regeneration layer. This could potentially limit current and future tree regeneration via competition (Ehrenfeld 1980; Metzger and Schultz 1984; Royo and Carson 2006). The observed trends suggest that tree density is declining in both the small and large regeneration layers in the partially harvested treatments. Intolerant tree species like aspen and paper birch are currently responsible for this trend. However, the trend of increasing shrub density in the small and large regeneration layers are opposite that of the trend of declining tree density, suggesting that if the directions of both trends continue in the future, shrubs could limit further tree regeneration (Ruel 1992; Archambault et al. 1998).

Management Implications and Conclusions

Based on nine years of post-treatment data, our study shows that active management of aspen-dominated Northern Hardwood riparian forests on rich soils can increase the regeneration of tree species compared to no-cut riparian buffers that are important commercially and ecologically in Northern Minnesota. The data show that increases in intolerant tree species occurred immediately and that tolerant species begin regenerating at a later period in partially harvested RMZs. Therefore, if tree reproduction is a management goal in RMZs, we conclude that no-cut riparian buffers do not lead to sufficient tree regeneration, even in the presence of an upland clearcut edge.

In this study, I found few differences in vegetation response between RMZ harvest method (CTL vs TL) from 1 to 9 years post harvest. There was a greater intolerant tree species density response in the TL treatment immediately post harvest. However, this difference did not carry on past the first year after treatment as there were no differences between TL and CTL in years 3 and 9. It is likely that the treatments had similar light availability and we assume this plays a greater role in vegetation development through time.

Partially harvesting in RMZs increased light availability sufficiently for the regeneration of intolerant species and also for the development of the advance regeneration of more tolerant species. The implementation of the partial cut in the RMZ portion of the stands created a gradient of removal intensity from stream to clearcut edge, with lowest harvest intensities closest to the streams. Thus, the harvest design preserved the riparian function gradient by maintaining mature forest closer to the stream (Palik et al. 2000) and created a structurally and compositionally diverse RMZ where both timber and non-timber management objectives were considered. Continued research at these sites is needed to further our knowledge as to what extent these objectives are being met over time.

The role of shrubs as potential competitors for important tree species is still unclear nine years post-treatment. This study might show the beginning of an increasing trend in shrub density in the woody regeneration layers in the partially harvested treatments, but only long-term data collection can confirm or refute this and help determine whether shrubs may pose serious competition with trees in the future. As of nine years post-treatment, considering moderate control of shrub species to ensure the continued recruitment of commercially important tree species into the overstory strata is recommended.

Table 1. Summary of live overstory trees (≥10 cm DBH) by treatment over time. Standard errors are noted in parentheses. NA indicates that data were not collected in that year but assumed to have stayed constant from the previous year. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years.

Time	**Full Control**	**Rip. Control**	**Cut-to-length**	**Tree-Length**
		Overstory Basal Area (m^2/ha)		
Pre-treatment	28.0 (2.0)^{A}	28.0 (2.0)^{A}	26.3 (2.0)^{A}	33.7 (2.0)^{A}
1 yr post-treatment	NA^{Aa}	NA^{Aa}	13.0 (1.7)^{Ba}	13.1 (1.7)^{Ba}
9 yrs post-treatment	28.0 (2.3)^{Aa}	20.4 (2.3)^{Ab}	5.9 (2.3)^{Bb*}	6.4 (2.3)^{Ba}
		Overstory Density (stems/ha)		
Pre-treatment	645.8 (70.9)^{A}	759.3 (70.9)^{A}	606.0 (70.9)^{A}	748.9 (70.9)^{A}
1 yr post-treatment	NA^{Aa}	NA^{Aa}	243.1 (71.2)^{Ba}	331.1 (71.2)^{Ba}
9 yrs post-treatment	597.5 (58.6)^{Aa}	504.4 (58.6)^{Ab}	120.3 (58.6)^{Ba}	193.2 (58.6)^{Bb}

b*: Cut-to-Length yr 1 and Cut-to-Length yr 9 are marginally significantly different.

Table 2. Measures of CWD volume and blowdown accumulation at year nine post-treatment. Back-transformed medians and 90% confidence limits (in parentheses) are noted for CWD volume. Means and Standard errors (in parentheses) are noted for blowdown accumulation. Different superscripts denote significant differences at the α = 0.10 level (pairwise comparison α = 0.1/6 = 0.017).

Treatment	**CWD Volume** **(m^3 ha^{-1})**	**Blowdown Accumulation % (of 1 yr post-treatment density)**
Full Control	60.8 (35.1 – 105.5)^{a}	8.3 (9.6)^{a}
Riparian Control	120.1 (69.2 – 208.3)^{a}	34.5 (9.6)^{b}
Cut-to-Length	135.8 (78.3 – 235.6)^{a}	47.0 (9.6)^{ab}
Tree-Length	122.1 (70.4 – 211.8)^{a}	40.1 (9.6)^{ab}

Table 3. Density of the overall sapling (2.5 – 9.9 cm DBH) tree layer and aspen saplings by treatment over time. Standard errors are noted in parentheses. Different superscript letters indicate significant differences at the alpha = 0.10 level. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years.

Time	**Full Control**	**Rip. Control**	**Cut-to-length**	**Tree-Length**
		Overall Sapling Density (stems/ha)		
Pre-treatment	491.5 (108.7)^{A}	352.9 (108.7)^{A}	531.3 (108.7)^{A}	512.4 (108.7)^{A}
9 yrs post-treatment	413.6 (108.7)^{Aa}	267.6 (108.7)^{Ba}	1043.5 (108.7)^{Cb}	823.8 (108.7)^{C*a}
		Aspen Sapling Density (stems/ha)		
Pre-treatment	0.0 (32.4)^{A}	0.0 (32.4)^{A}	0.0 (32.4)^{A}	0.0 (32.4)^{A}
9 yrs post-treatment	1.2 (32.4)^{Aa}	28.6 (32.4)^{Aa}	273.9 (32.4)^{Bb}	28.6 (32.4)^{Bb}

C*: Tree-length yr 9 and Control 9 are marginally significantly different

Table 4. Density of the overall large regeneration layer (tree and shrub species greater than 1 m tall and less than 2.5 cm at DBH) by treatment over time measured in stems/ha. Standard errors are noted in parentheses. Different superscript letters indicate significant differences at the alpha = 0.10 level. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data was not compared to post treatment time periods.

Time	**Full Control**	**Rip. Control**	**Cut-to-length**	**Tree-Length**
Pre-treatment	3000 (2508)^{A}	1644 (2508)^{A}	3908 (2508)^{A}	2044 (2508)^{A}
1 yr post-treatment	4777 (2508)^{Aa}	2738 (2508)^{Aa}	3355 (2508)^{Aa}	5469 (2508)^{Aa}
3 yrs post-treatment	2627 (2179)^{Aa}	4683 (2179)^{Aa}	19012 (2179)^{Ab}	15079 (2179)^{Ab}
9 yrs post-treatment	4281 (3387)^{Aa}	7134 (3387)^{Aa}	23435 (3387)^{Ab}	21437 (3387)^{Ab}

Table 5. Density of the overall small regeneration layer (tree and shrub species combined, less than 1m tall) by treatment over time measured in stems/ha. Standard errors are noted in parentheses. Different superscript letters indicate significant differences at the alpha = 0.10 level Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data was not compared to post treatment time periods.

Time	**Full Control**	**Rip. Control**	**Cut-to-length**	**Tree-Length**
Pre-treatment	210713 (46081)^{A}	155519 (46081)^{A}	221498 (46081)^{A}	186000 (46081)^{A}
1 yr post-treatment	154571 (38690)^{Aa}	154057 (38690)^{Aa}	210341 (38690)^{Aa}	186485 (38690)^{Aa}
3 yrs post-treatment	110970 (22295)^{Aa}	97113 (22295)^{Aa}	82839 (22295)^{Aa}	79182 (22295)^{Aa}
9 yrs post-treatment	164077 (31341)^{Aa}	138981 (31341)^{Aa}	121414 (31341)^{Aa}	91939 (31341)^{Aa}

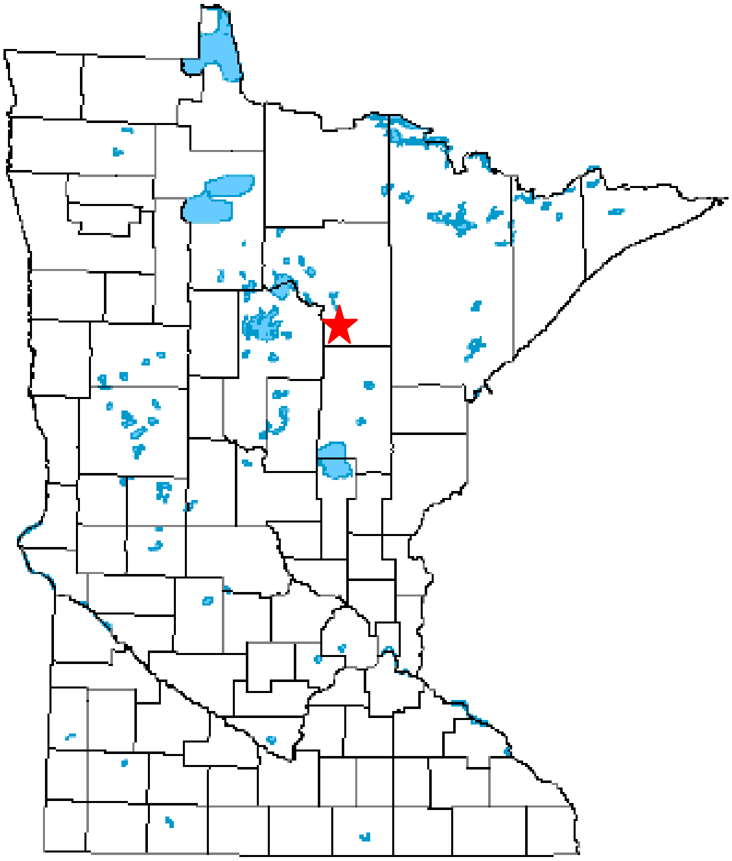

Figure 1. Star indicates location of study site within Minnesota (Map source: MNDNR website).

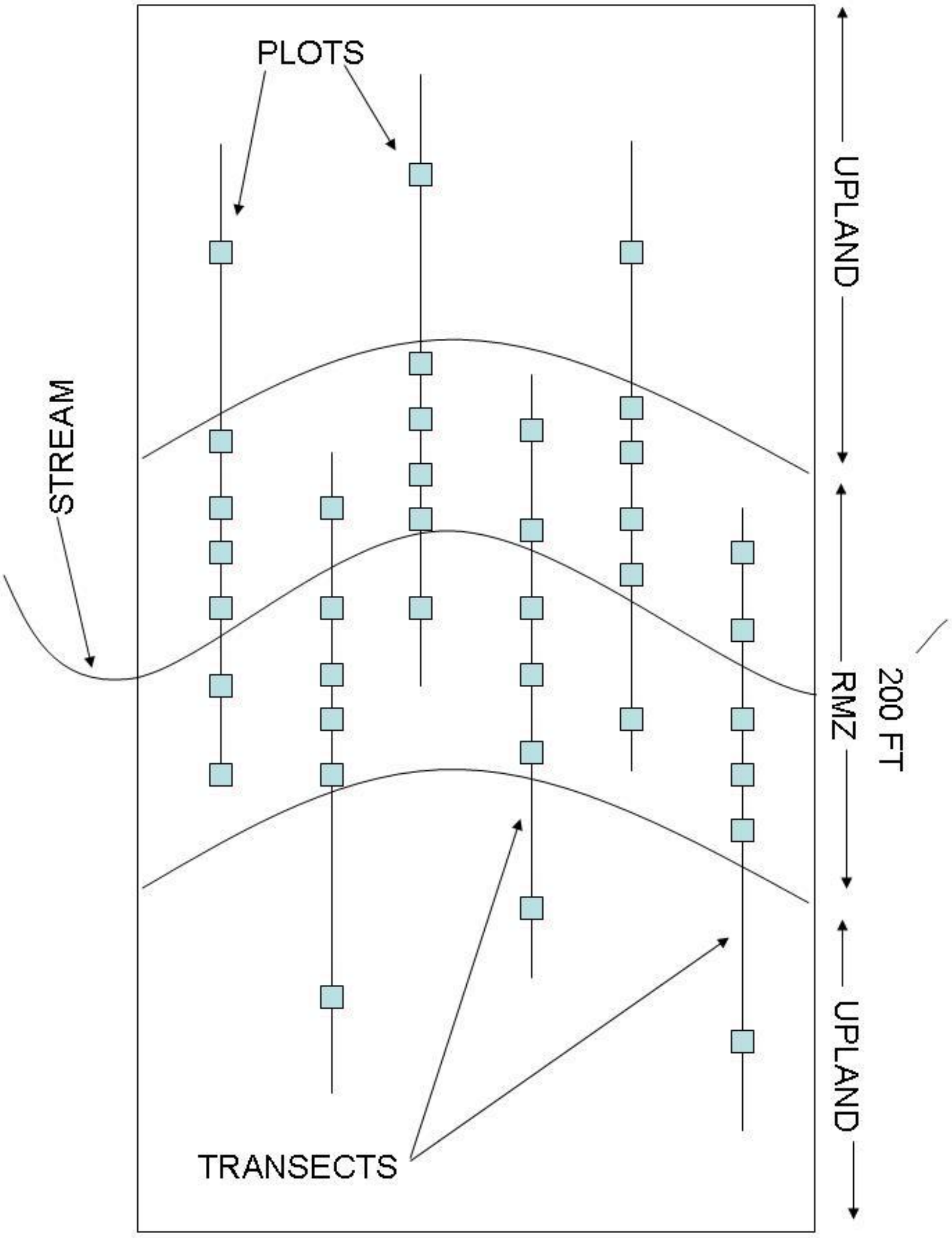

Figure 2. Depiction of design and plot layout of the 12 stands in this study. Full Control treatments (3 stands) had RMZs and Upland sections that were unharvested; the Riparian Control treatments (3 stands) had RMZs that were unharvested and Upland sections that were clearcut; and the Tree Length (TL) and Cut-to-Length treatments (3 stands each treatment) had RMZs that were partially harvested and Upland sections that were clearcut.

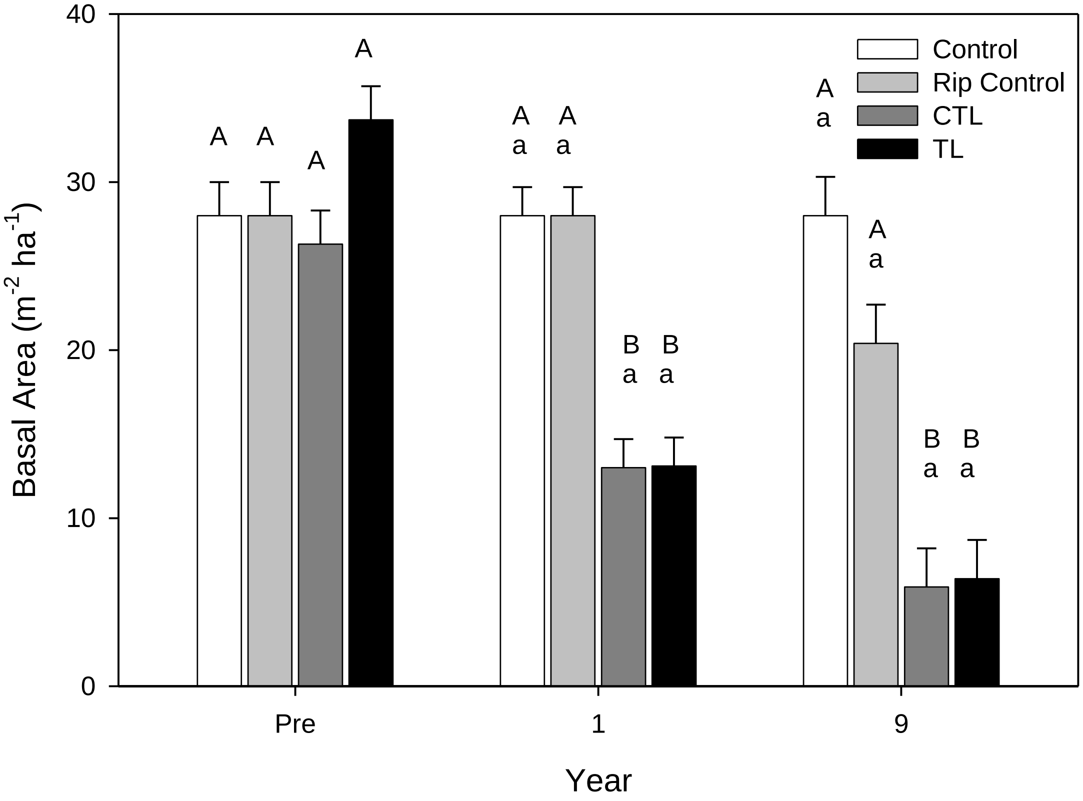

Figure 3. Basal Area of the overstory trees (DBH ≥ 10 cm) represented in m^{-2} ha^{-1}. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

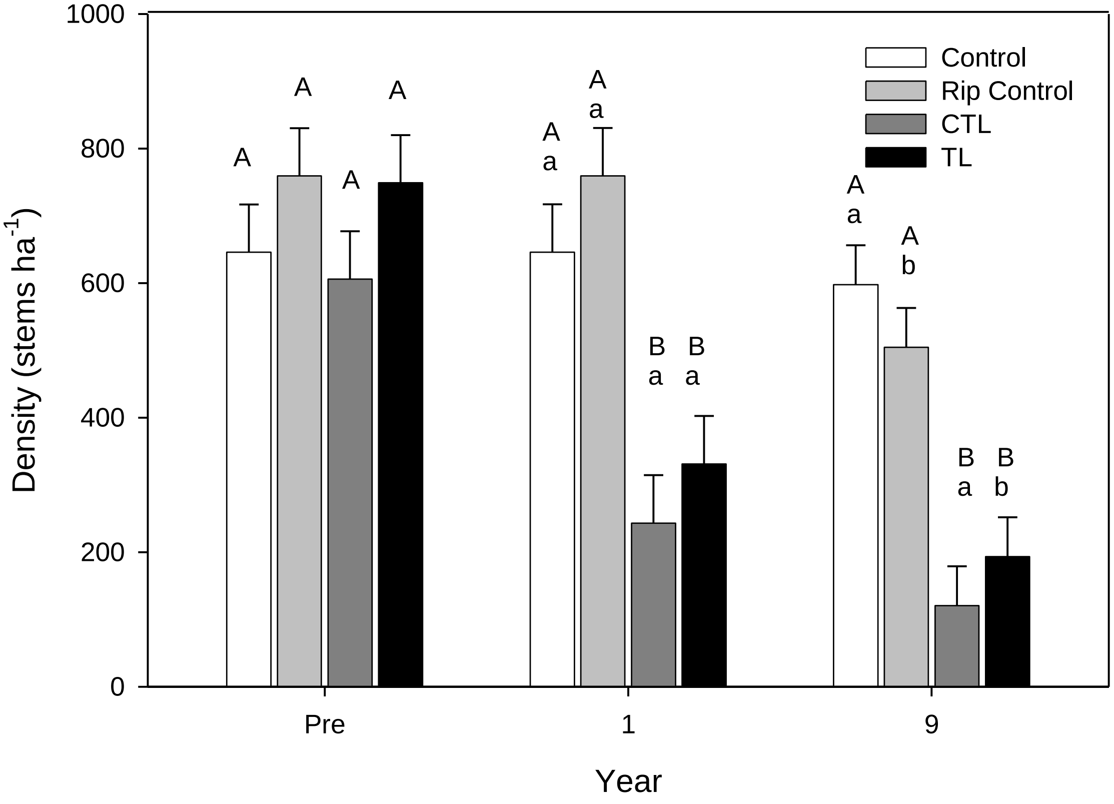

Figure 4. Density of the overstory trees (DBH ≥ 10 cm) represented in stems ha^{-1}. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

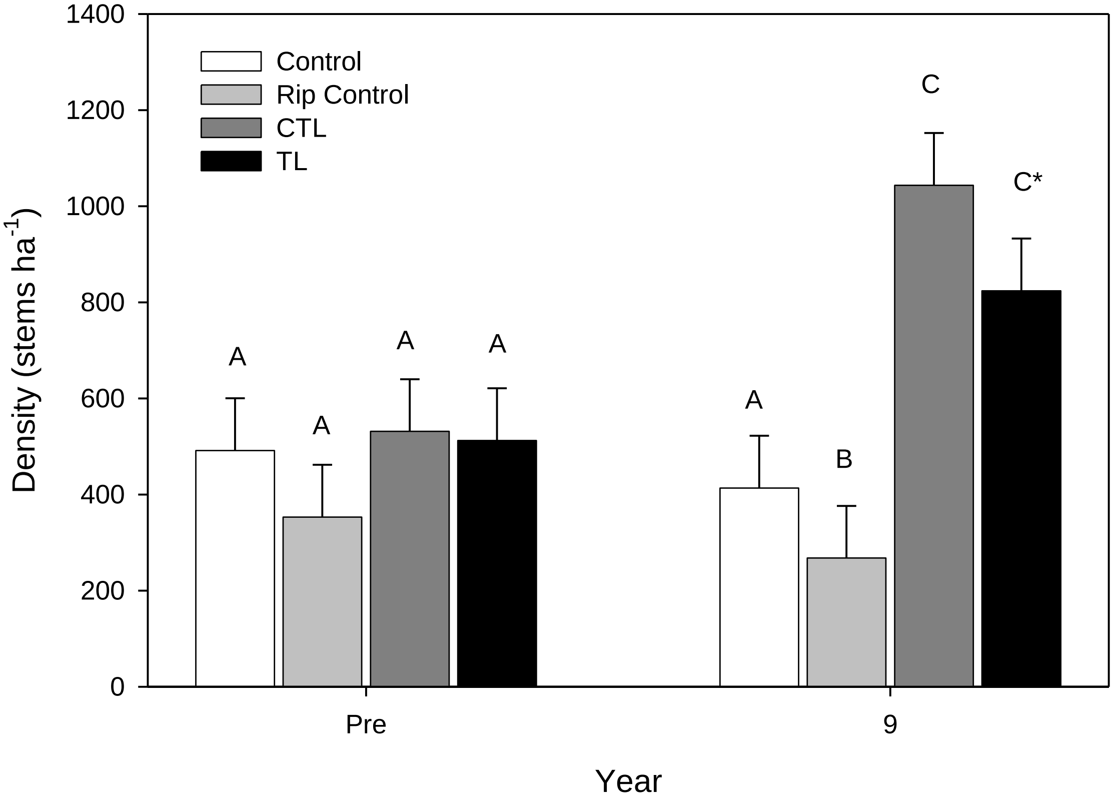

Figure 5. Density of the sapling trees (DBH between 2.5 – 9.9 cm) represented in stems ha^{-1}. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

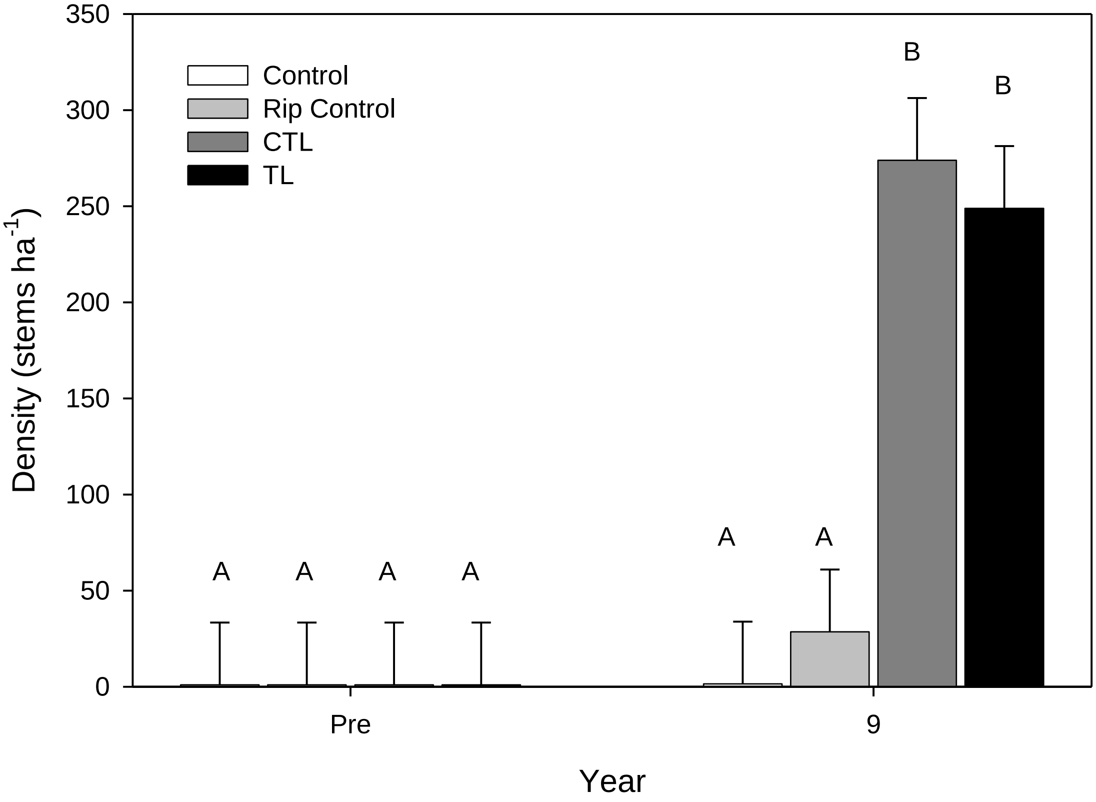

Figure 6. Density of the aspen (*Populus tremuloides* and *P. grandidentata*) in the sapling layers (DBH between 2.5 – 9.9 cm) represented in stems ha^{-1}. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

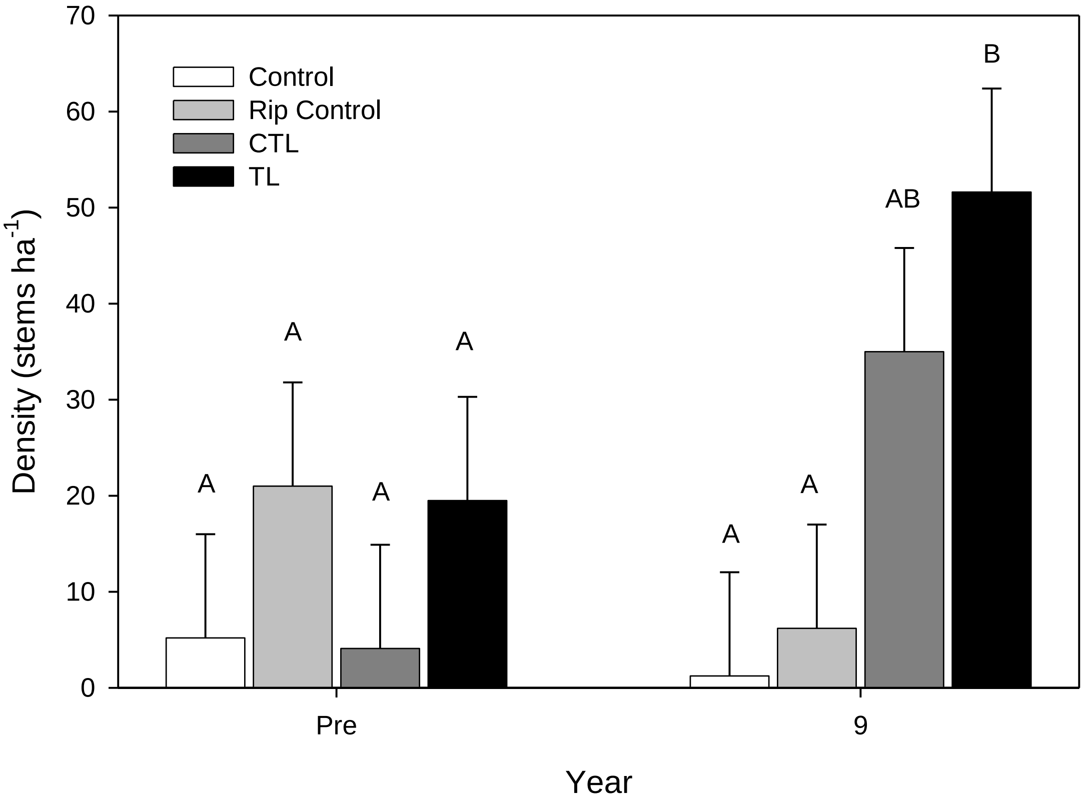

Figure 7. Density of the paper birch (*Betula papyrifera*) in the sapling layers (DBH between 2.5 – 9.9 cm) represented in stems ha^{-1}. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

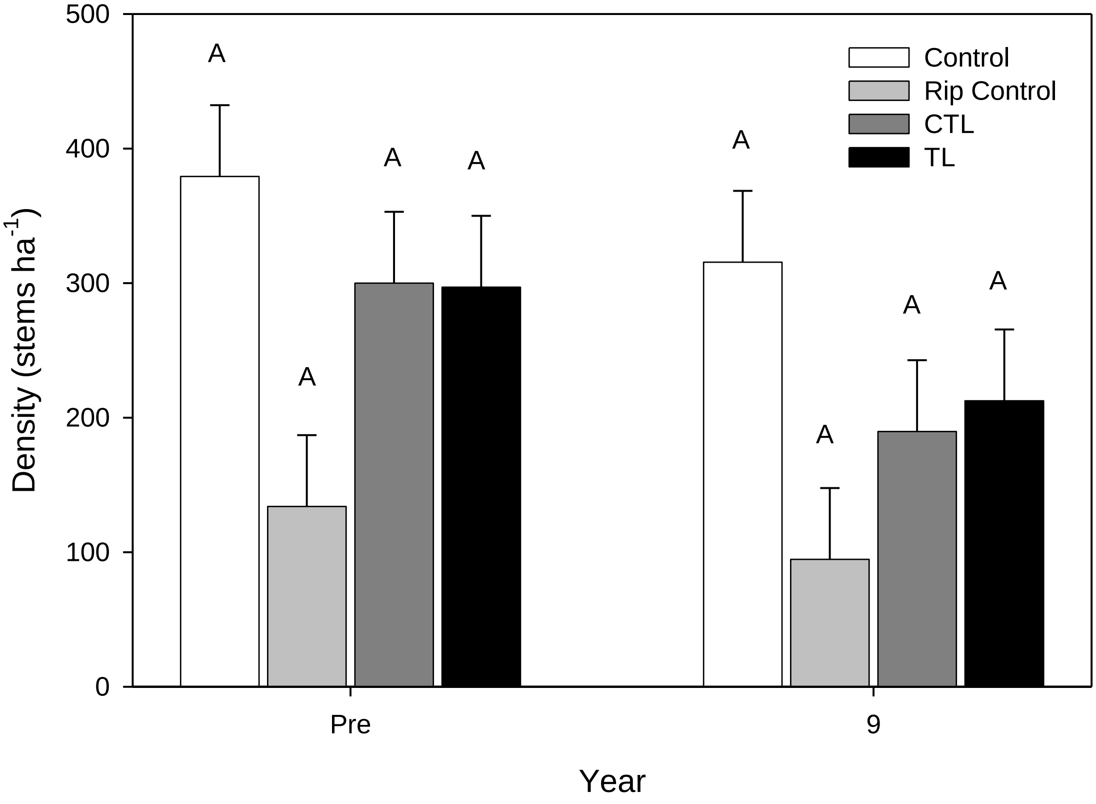

Figure 8. Density of the sugar maple (*Acer saccharum*) in the sapling layers (DBH between 2.5 – 9.9 cm) represented in stems ha^{-1}. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

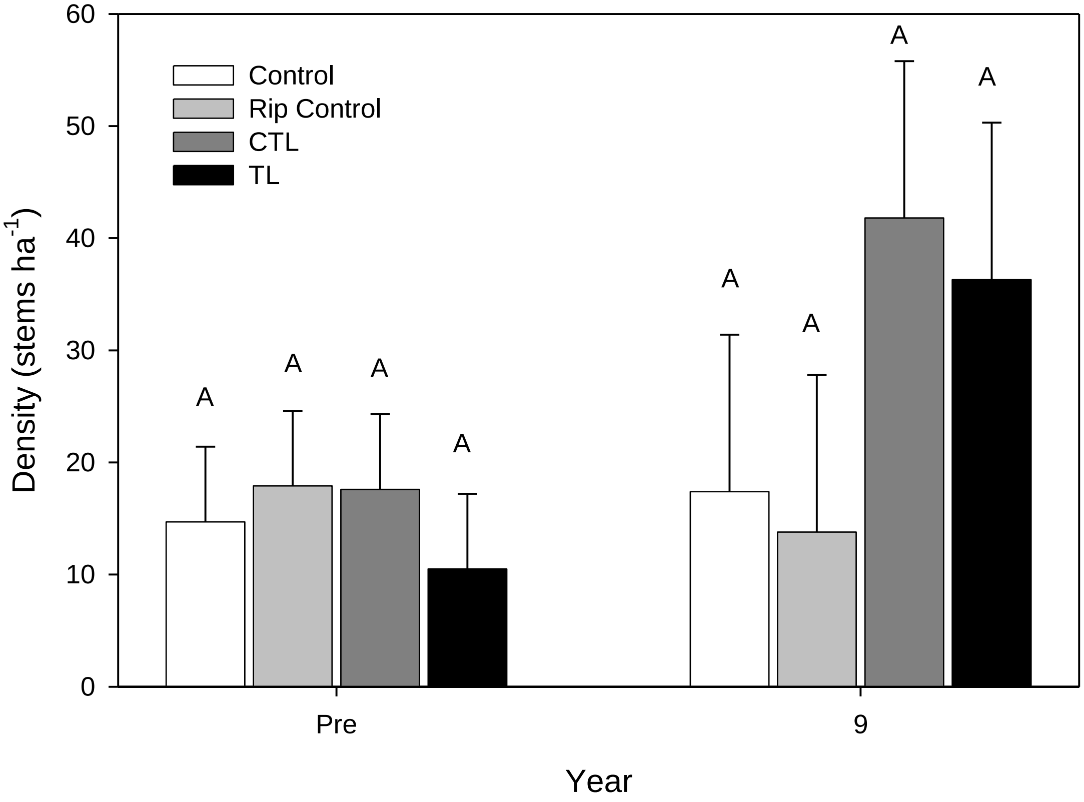

Figure 9. Density of the American basswood (*Tilia americana*) in the sapling layers (DBH between 2.5 – 9.9 cm) represented in stems ha^{-1}. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

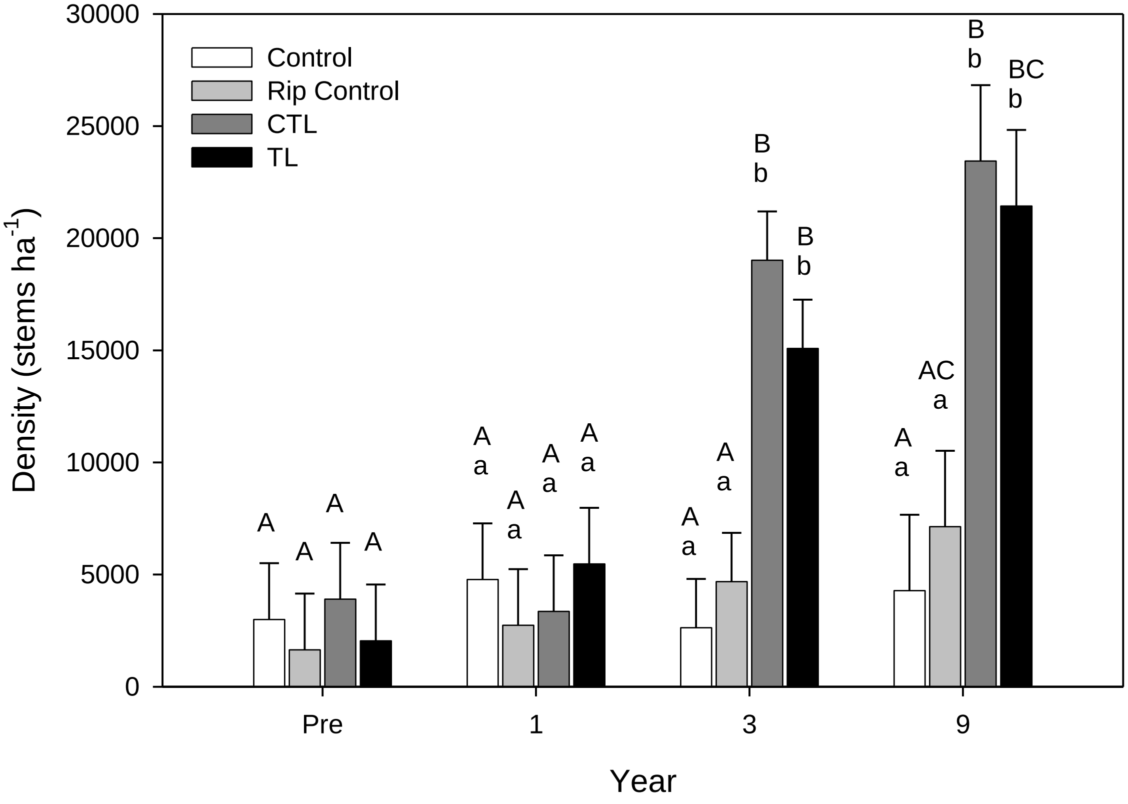

Figure 10. Overall density of the large regeneration layer by treatment over time. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

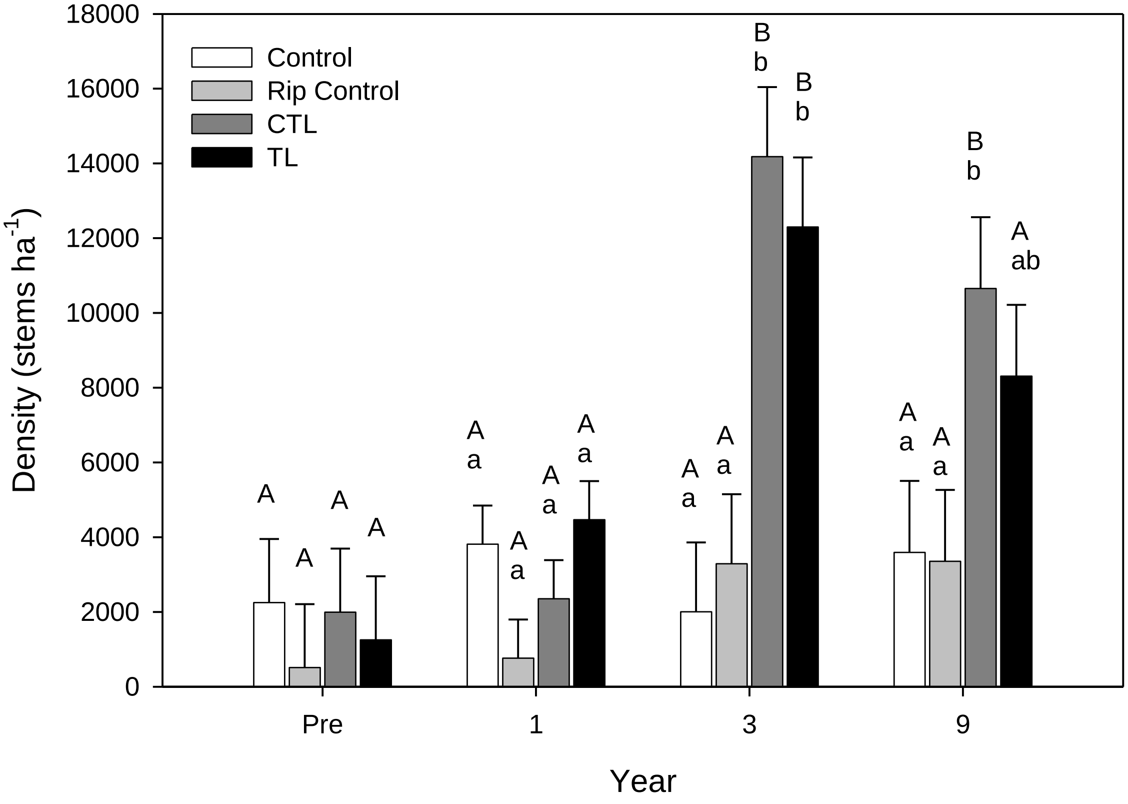

Figure 11. Density of tree species in the large regeneration layer by treatment over time. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

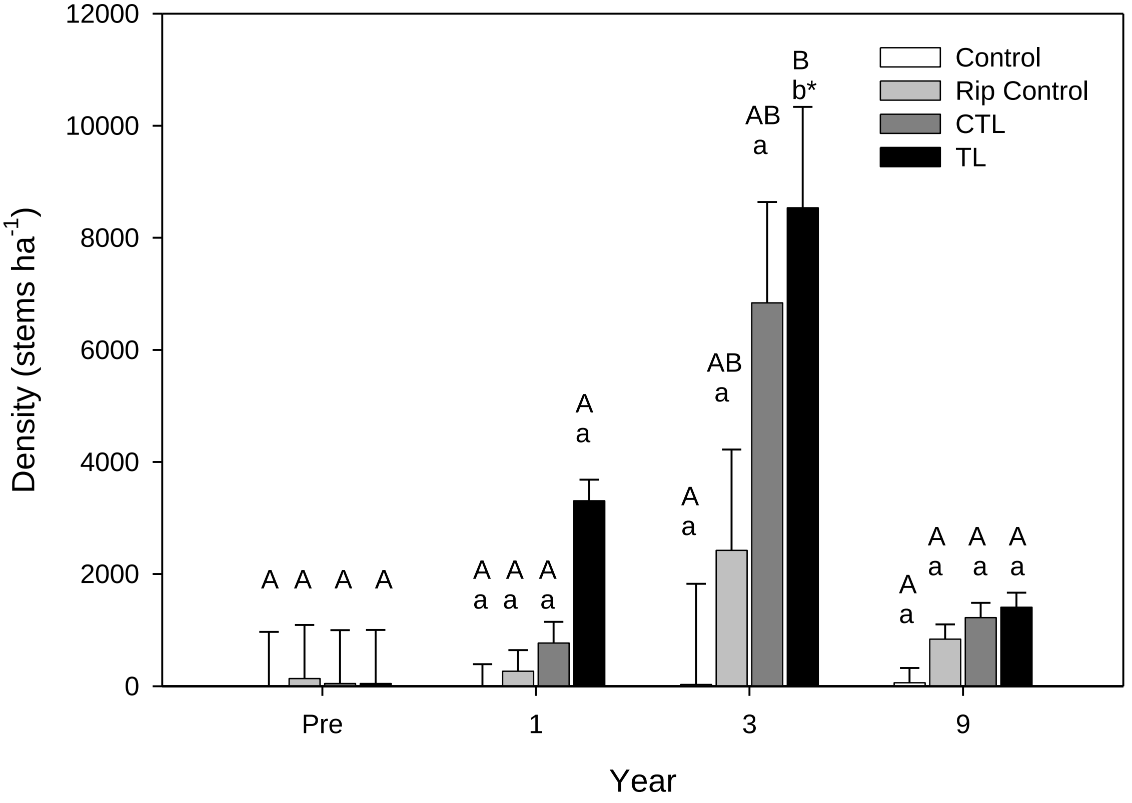

Figure 12. Density of aspen (*Populus tremuloides* and *P. grandidentata*) in the large regeneration layer by treatment over time. Error bars represent + 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

b*= TL3 is only marginally greater than TL1

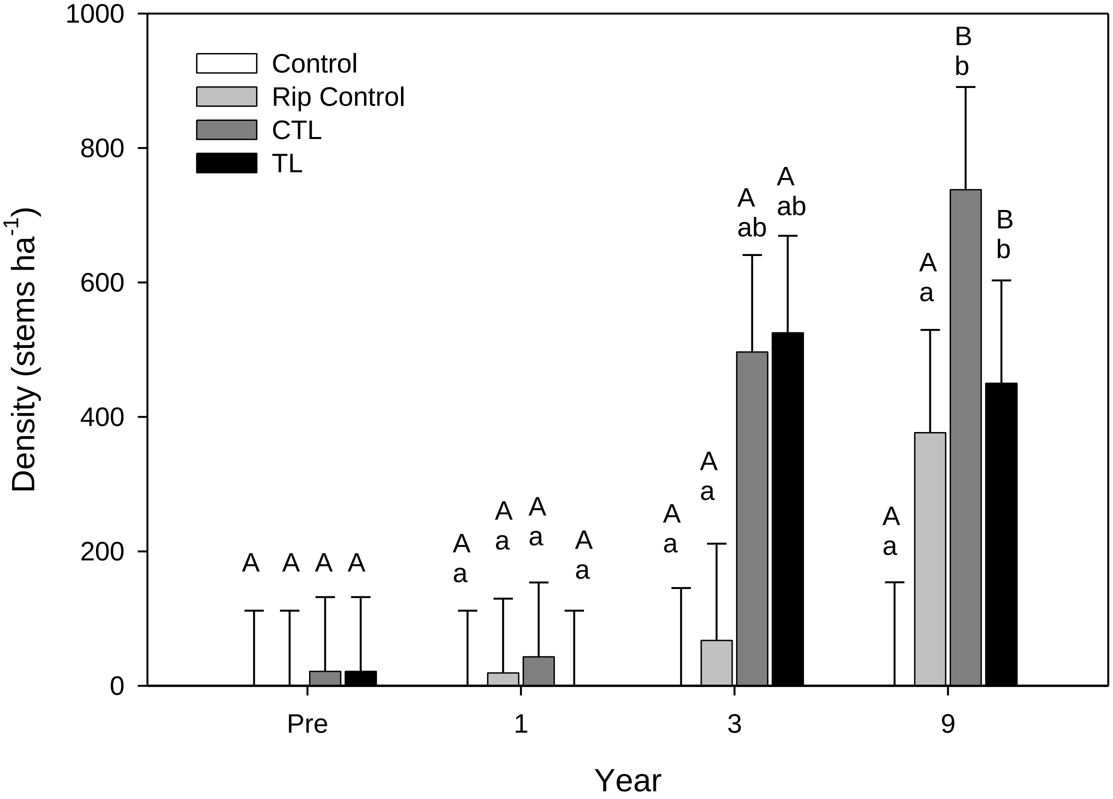

Figure 13. Density of paper birch (*Betula papyrifera*) in the large regeneration layer by treatment over time. Error bars represent + 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

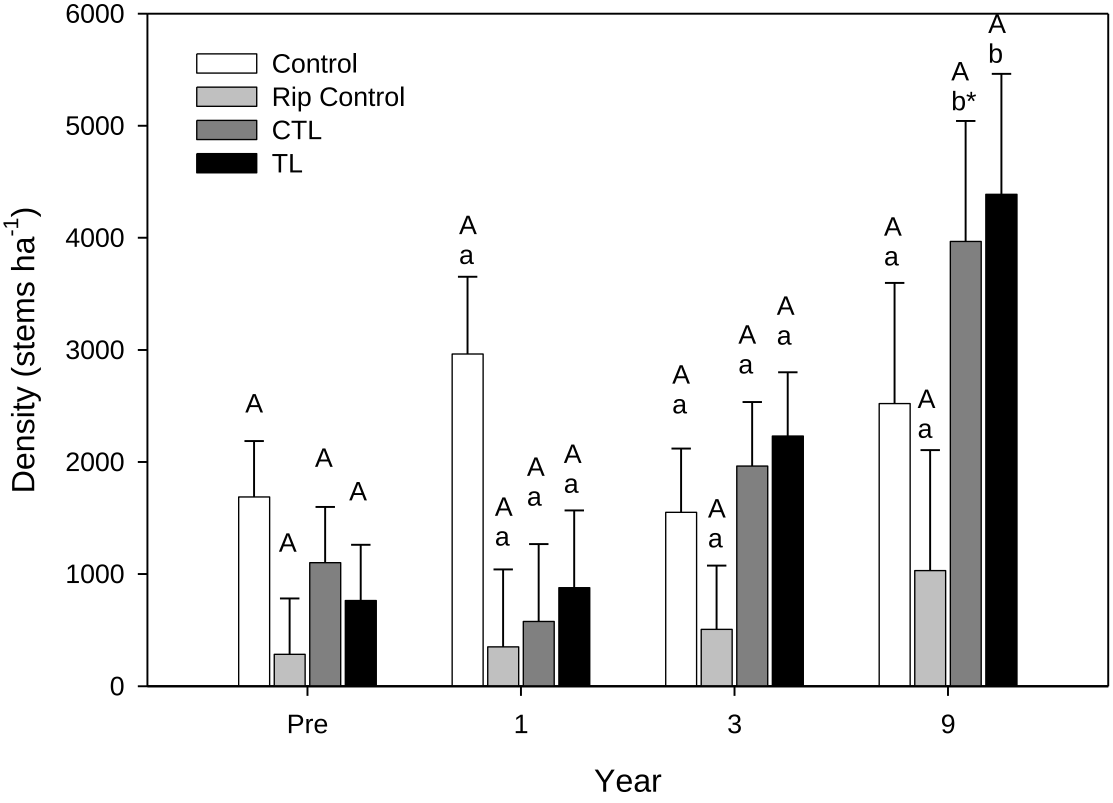

Figure 14. Density of sugar maple (*Acer saccharum*) in the large regeneration layer by treatment over time. Error bars represent + 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

*b = CTL9 is only marginally greater than CTL3 but significantly greater than CTL1

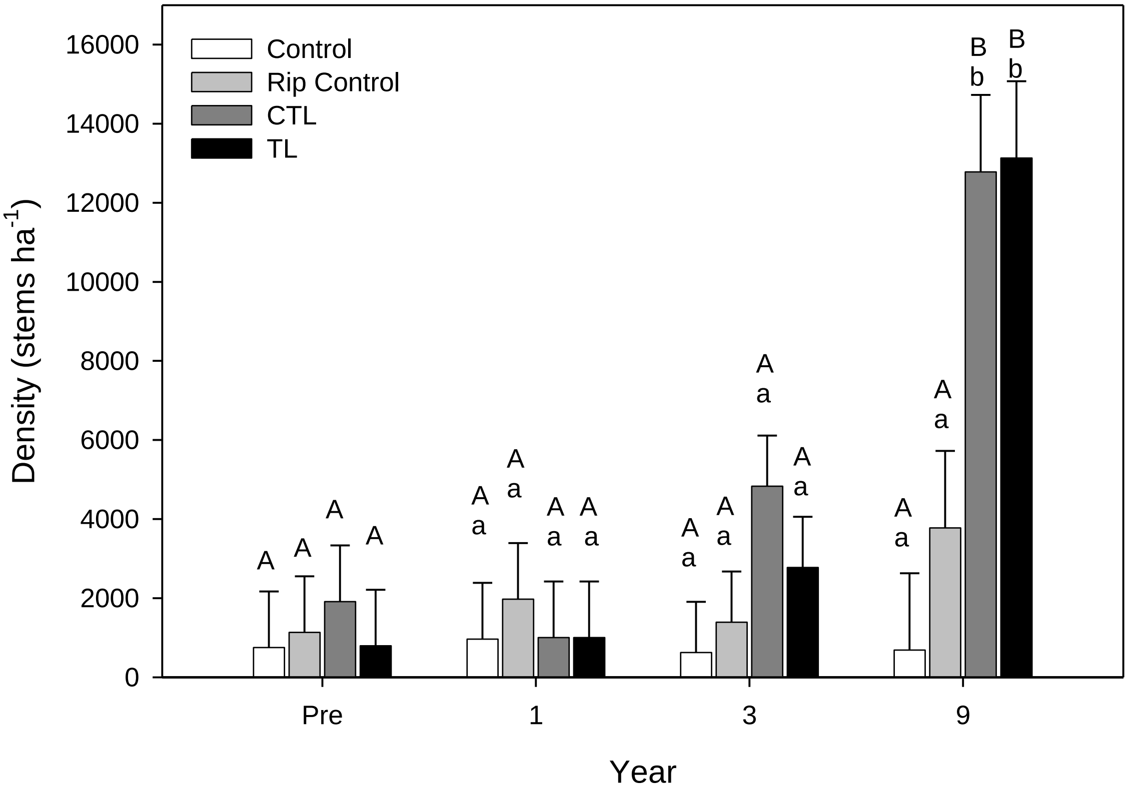

Figure 15. Density of shrub species in the large regeneration layer by treatment over time. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

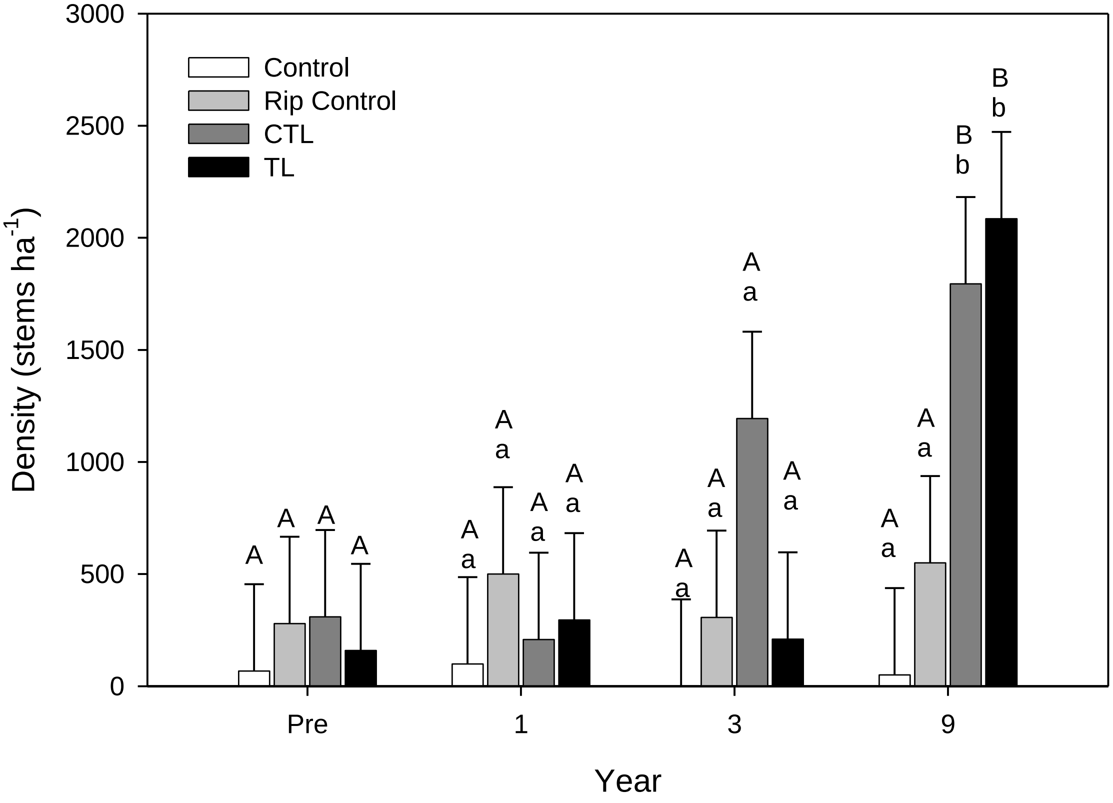

Figure 16. Density of mountain maple (*Acer spicatum*) in the large regeneration layer by treatment over time. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

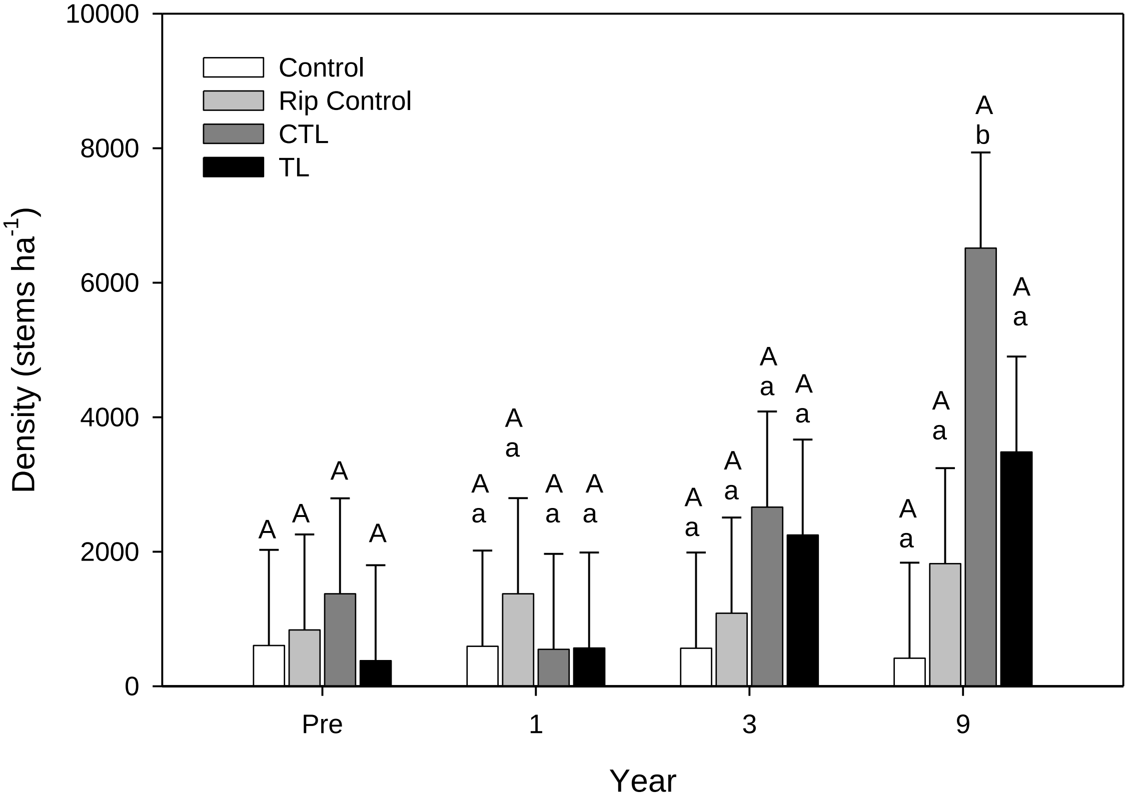

Figure 17. Density of hazel (*Corylus* spp.) in the large regeneration layer by treatment over time. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

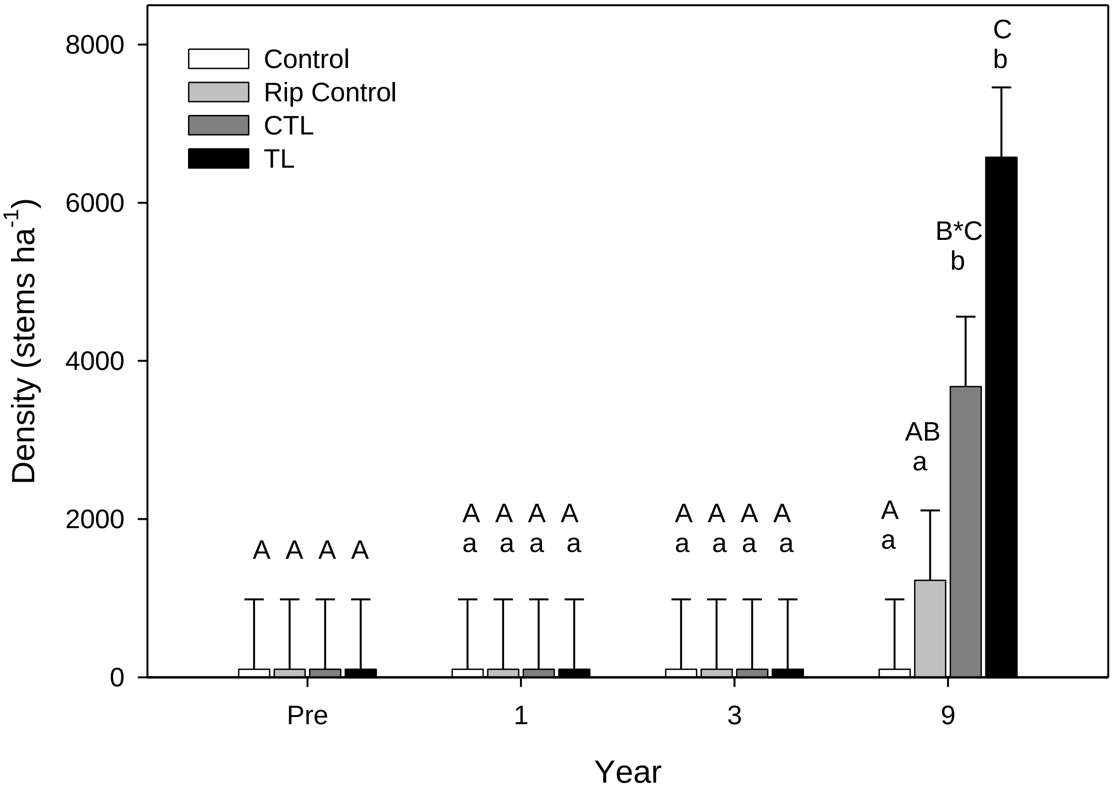

Figure 18. Density of raspberry (*Rubus* spp.) in the large regeneration layer by treatment over time. Error bars represent ± 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

B* = CTL9 is marginally greater than Control9 and is not significantly different than riparian Control9

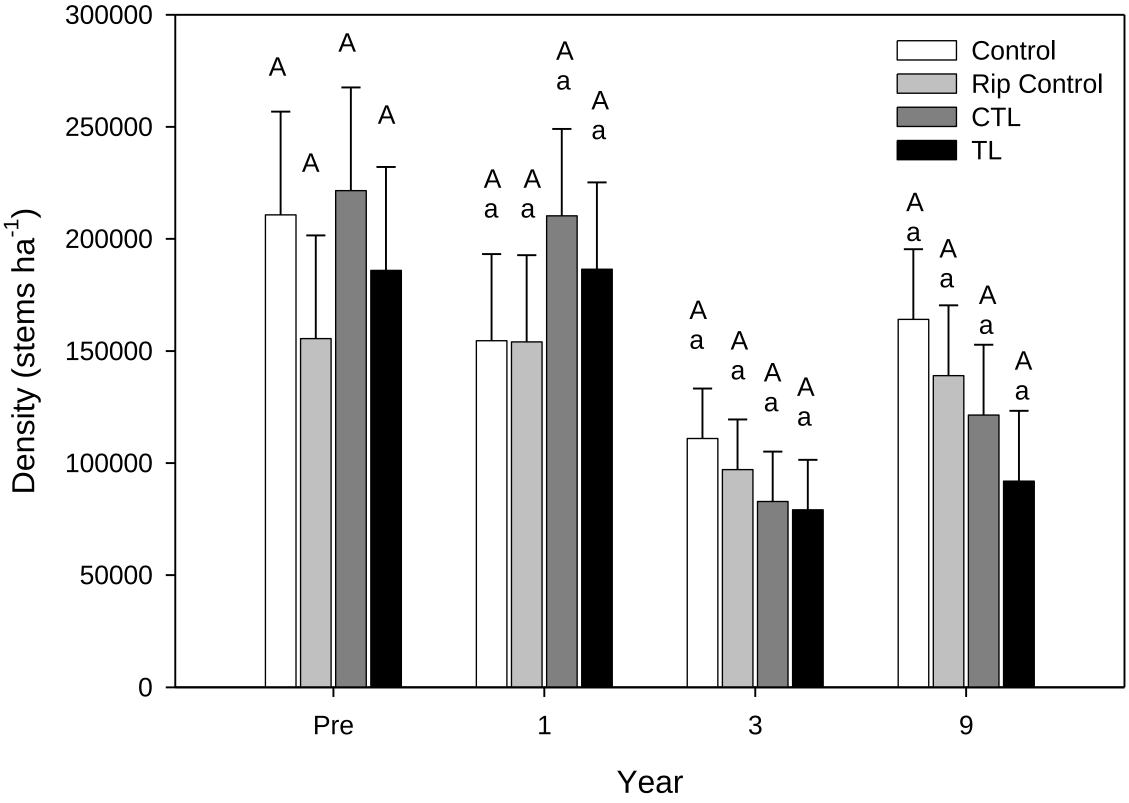

Figure 19. Overall density of the small regeneration layer by treatment through time. Error bars represent + 1SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

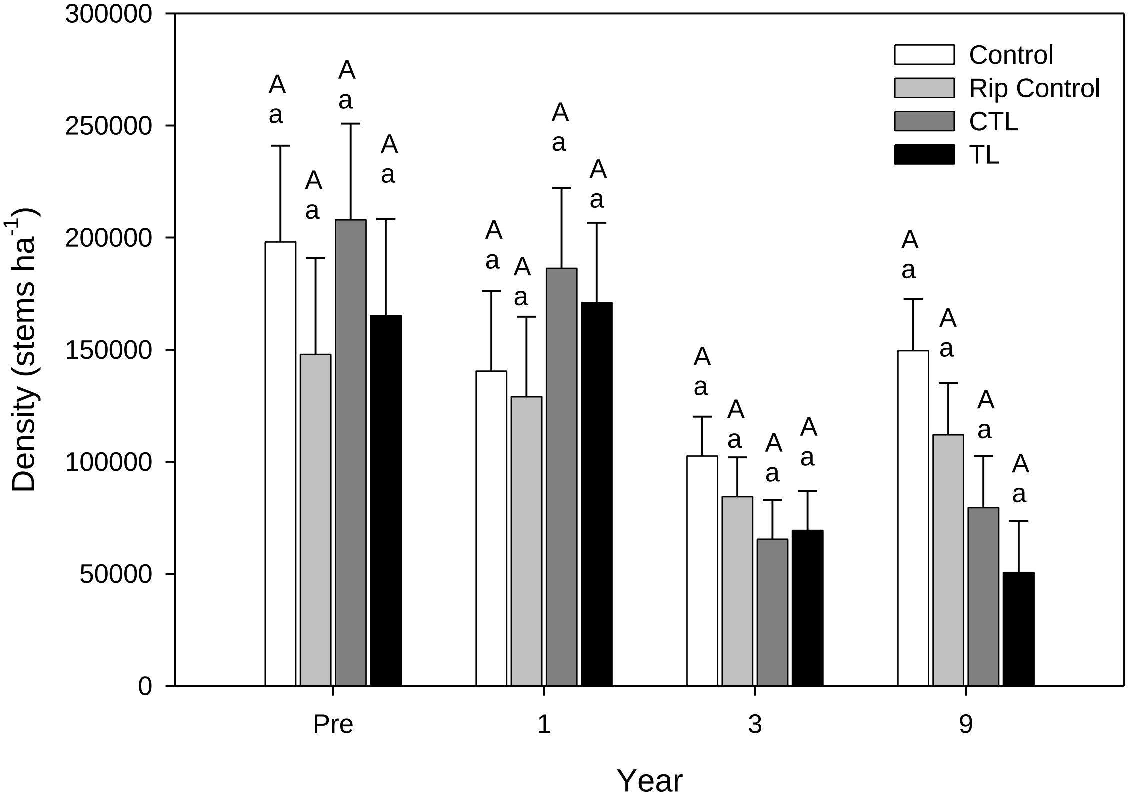

Figure 20. Density of the tree species in the small regeneration layer by treatment over time. Error bars represent + 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

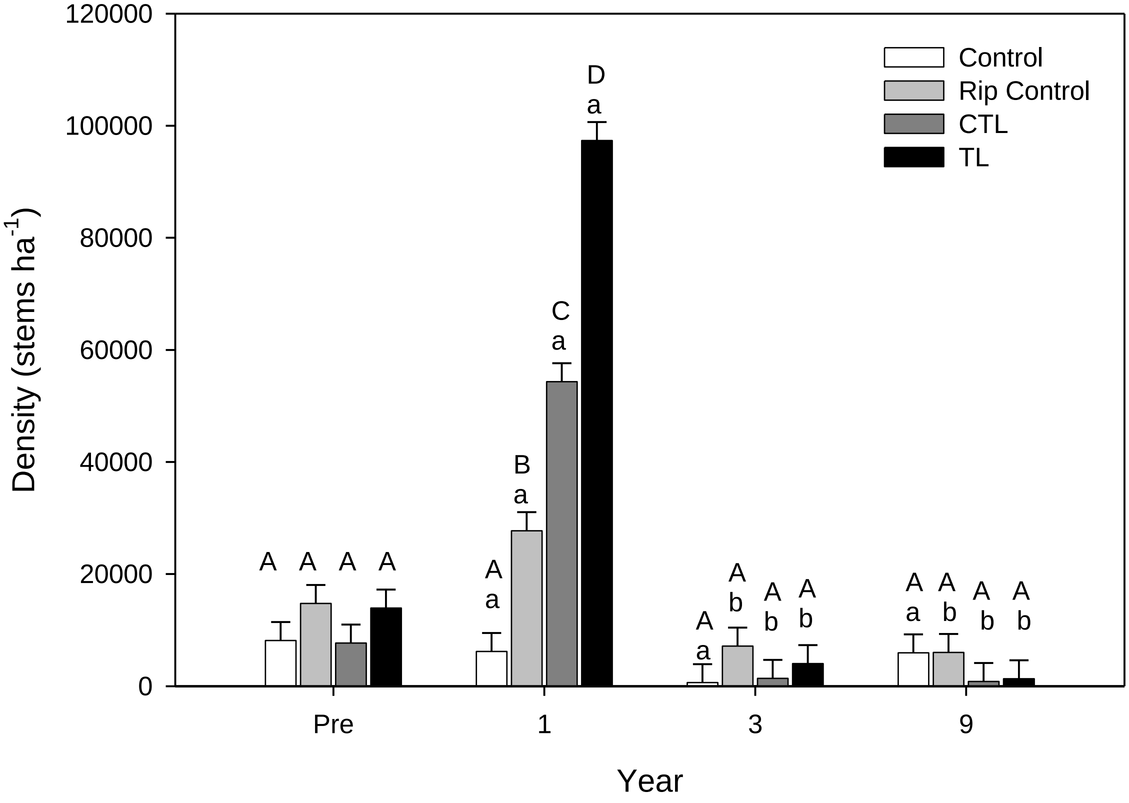

Figure 21. Density of the aspen (*Populus tremuloides* and *P. grandidentata*) in the small regeneration layer by treatment over time. Error bars represent + 1 SE. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

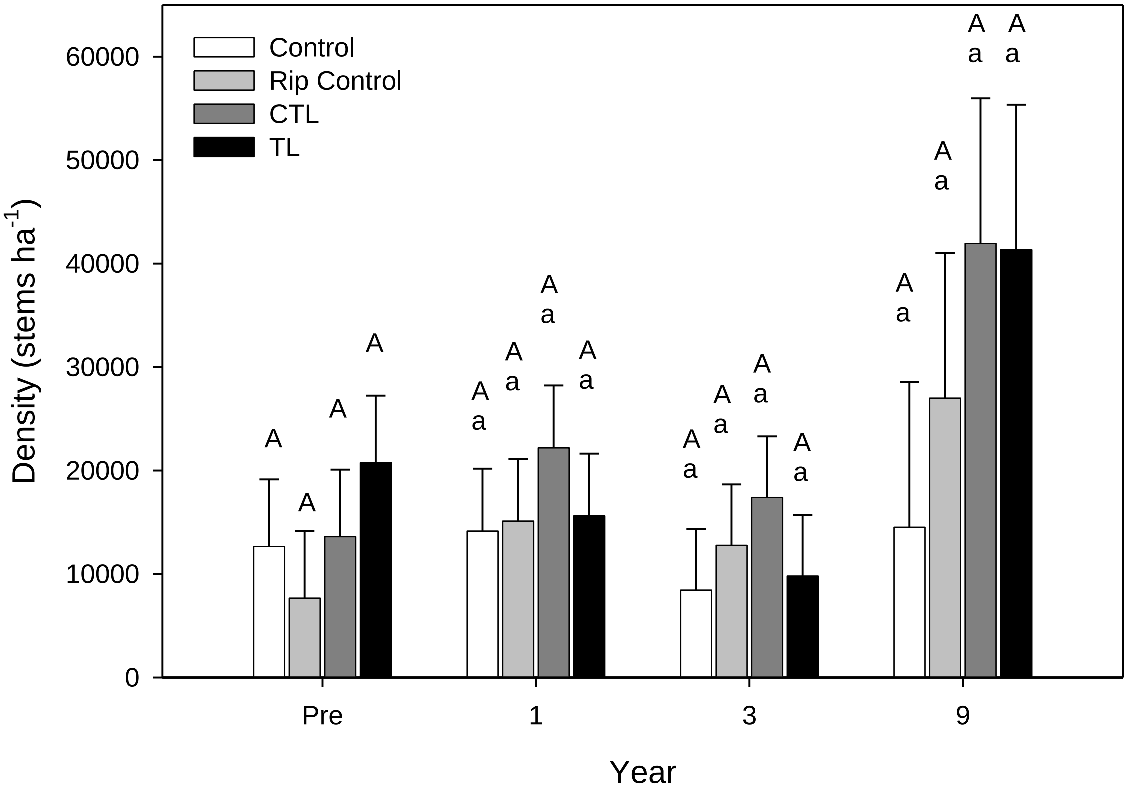

Figure 22. Density of shrub species in the small regeneration layer by treatment through time. Error bars represent + 1 SE. The density in the TL treatment was significantly higher in year nine than in year three (p = 0.008). Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

CHAPTER TWO:

Effect of harvest method on understory plant community composition and abundance in Riparian Management Zones, in Northern Minnesota, USA.

INTRODUCTION

Establishing and evaluating forestry practices that balance timber production with ecological values are important for the protection of biological diversity and the overall functioning of forest ecosystems (Roberts and Gilliam 1995b; Perry 1998; Simberloff 2001). Riparian areas, spaces in the landscape where aquatic and upland terrestrial ecosystems interact, are especially important for wildlife habitat, filtering and storing sediment and nutrients, maintaining plant biodiversity, timber harvesting, and recreational activities, such as fishing and hunting (Gregory et al 1991; Gilliam 1994).

Riparian plant communities are vital to protecting the link between terrestrial and aquatic ecosystems (Gregory et al. 1991; Crow et al. 2000; Hornbeck and Kochenderfer 2000; Boothroyd et al. 2004). Riparian plants are important in shading adjacent water bodies, stabilizing the soil, inputting organic matter in the form of litter and coarse woody debris, and regulating water yield (Hornbeck and Kochenderfer 2000; Stewart et al. 2000). Owing to its sensitivity to forest management and its overall importance to forest ecosystems, understory flora has been the focus of much research on evaluating forest management practices and silvicultural prescriptions in upland ecosystems (Metzger and Schultz 1981; Duffy and Meier 1992; Halpern and Spies 1995; Meier et al. 1995). There is strong evidence that timber harvesting can cause dramatic changes to the overstory tree layer and that overstory removal can change understory plant community composition and abundance of upland forests (e.g., Fredericksen et al. 1999; Gilliam et al. 1995;

Schumann et al. 2003; Battles et al. 2001; Halpern et al. 2005; Kern et al. 2006). As important as riparian vegetation is, however, research on how partial timber harvesting affects understory plant composition and abundance in riparian areas is scarce.

In 1997, a riparian area management study was started to compare plant responses in partially harvested and unharvested Riparian Management Zones (RMZs), both with adjacent clearcut uplands. Approximately 60% of the basal area was harvested in the RMZ portions of the partially harvested RMZ treatments. However, further overstory reductions occurred over nine years of the post-treatment sampling period in both the partially harvested and unharvested treatments. In the harvested RMZs, overstory density decreased by 50% and basal area by 56% over the nine year post-treatment sampling period. In comparison, the unharvested RMZs overstory density decreased by 30% and basal area by 23%. Consequently, understory trees, especially shade intolerant aspen (*Populus spp = P. tremuloides* Michx., *P. grandidentata* Michx, and *P. balsamifera* L.) and paper birch (*Betula papyrifera* Marsh.) had greater regeneration stem densities in partially cut than in uncut RMZs 9 years post-treatment (Chapter 1).

In addition to greater amounts of tree regeneration in the partially harvested treatments, shrub densities increased as well. In this chapter, I will explore to what extent the overstory disturbance from harvesting and subsequent blowdown has changed the understory plant community. These results may have important implications for forest management, as plants growing in the lower forest strata can be important site indicators. More specifically, I am interested in comparing the species composition and abundance of woody and herbaceous layers in these differently managed RMZs over time. I hypothesize that the species composition between harvested and unharvested RMZs will be different and that unharvested RMZs will have greater abundances of shade intolerant and disturbance indicating species. Additionally, I expect greater abundances of woody and herbaceous species in the harvested compared to unharvested RMZs due to greater light availability.

METHODS

Study Area

The study area is located in the Laurentian Mixed Forest Province (MN DNR 2003) in southern Itasca County, Minnesota (47° 8' 1.298" N, 93° 37' 37.773" W) on land owned and managed by UPM Blandin Paper Company (Figure 1.1). These forests are within the Northern Minnesota Drift and Lakes Section and located in the St. Louis Moraines Subsection. The annual precipitation in this area ranges from 61-69 cm, 40% of which occurs during the 111 to 131 day growing season (MNDNR 2003). Average winter temperature (December – March) is -10.6° C and average summer temperature (June – September) is 16.7° C (MNDNR 2004). The forest community is a Northern Rich Mesic Hardwood Forest (MHn47), which is characterized by loamy, calcareous soils that are well-drained to somewhat poorly-drained, derived from end moraine, and occurs mostly in isolated patches. Windthrow is an important natural disturbance in these forest types (MNDNR 2003). All experimental units are secondary upland and riparian forests ranging in age from 70-120 years prior to treatment. The dominant tree species (in order of relative basal area) include aspen (13-24% relative basal area (RBA) and 7-10% relative density (RD)), sugar maple (*Acer saccharum* Marsh.; 8-22% RBA and 14-32% RD), paper birch (10-19% RBA and 13-20% RD), and basswood (*Tilia Americana*

L.; 1-15% RBA and 2-15% RD). Northern white-cedar (*Thuja occidenalis* L.) and black ash (*Fraxinus nigra* Marsh.) become more dominant at the stream edge.

Experimental Design

Twelve experimental units were established in 1997. These units were centered along first order streams (~1 m in width) that drain into Pokegama Lake. The units have a north-south orientation and are each approximately 4.86 ha in size. A buffer of at least 100 m separates treatment units that occur on the same stream. A Riparian Management Zone (RMZ) was designated in each unit that runs the width of the unit. The RMZ was centered on the stream (extending 33 m on each side) and its boundary was in upland forest. A slight elevational gradient of topographical features (fluvial landforms) extended from the stream to the upland and included stream floodplains, slopes, and terraces. Landform types and sizes were variable among units.

The experiment used a complete randomized design consisting of four treatments that were randomly assigned to each of three replicates. The four treatments include (1) a Full Control (no harvesting); (2) a Riparian Control consisting of an uncut RMZ with an adjacent upland clear cut; and two RMZ partial cut treatments using either (3) a traditional tree-length harvesting (TL) and (4) a cut-to-length harvesting (CTL). In both partially cut RMZ treatments overstory trees ($\geq$ 10 cm diameter at breast (1.37 m) height (DBH)) were harvested to a residual basal area of 12 m^2 ha^{-1} (60 % removal); the adjacent uplands were clearcut and harvested with the same method as their RMZ counterparts. Upland areas adjacent to Riparian Controls were harvested using the CTL method. Harvesting was conducted in the late summer to early fall of 1997. In addition blowdown that occurred over the nine year post-treatment period reduced overstory density by 30% and 50% of the first year post-treatment density in the Riparian Control and partially harvested treatments (Chapter 1).

Sampling Design

In each unit, five to eight transects were established perpendicular to the stream (81 transects in total). Five to eight permanent plot centers (437 total) were placed in the center of each fluvial landform (i.e., floodplain, slope, terrace) on each transect, one point was generally established in the upland within the RMZ, and one in the upland outside of the RMZ. Each transect crossed the stream and plots were established on both sides of the stream such that at least one to two plots generally occurred on one side (the short side of transect) and four to six plots occurred on the opposite side (long side of transect). Short and long sides of each transect usually alternated on the north and south side of the stream. Because plots were placed in different fluvial landforms, distances between plots varied due to inherent topographic variation. Permanent plots centers were marked with metal stakes in 1997 and, if necessary, re-monumented in the summers of 2005 and 2006 or re-established if not found (30 plots total). At each permanent plot center, vegetation sampling included overstory trees (≥ 10 cm DBH), tree saplings (≥ 2.5 cm DBH), large woody regeneration (>1m tall and < 2.5 cm DBH), small woody regeneration (≤1 m tall), and herbaceous vegetation.

Vegetation Sampling

To describe the composition and abundance of the overstory and sapling layers before and after harvest, trees were sampled in 1997 (pre-harvest) and in 2006 (nine years post-harvest) by the point-quarter method (following Brower and Zar 1984) in all stands. In 1998, (one year post-harvest), trees in the overstory layers were censused in the RMZ portions of the CTL and TL stands only. Saplings were not censused one year after harvest as it was assumed that there was no change from harvesting. Overstory and sapling density and basal area (1997 and 2006) for all species combined and by species were computed for each treatment following Mitchell (2006). Density and basal area (1998) were computed with known area estimates of each stands' RMZ (Table 1).

Large and small woody regeneration sampling was conducted during the summers of 1997 and after harvest in the summers of 1998, 2000 (three years post-harvest), and 2006 following sampling methods described in Palik et al. (2003). Large woody regeneration was sampled in 1.5 m radius circular plots that were centered at each permanent plot center. Species and number of stems were recorded for each individual within the plot. Small woody regeneration was sampled in 0.5 m^2 square plots that were off-set by 1 m from the permanent plot center. The direction of the offset was determined by location of the stream side such that plots on the north side of the stream were located 1 m north of plot center and those on the south side of the stream were located 1 m south of plot center. Individuals were identified to species and number of stems was recorded. The density of each regeneration layer was summarized by treatment for each time period sampled.

Herbaceous plants were sampled in 1997, 1998, and 2006 in the same plots as the small woody regeneration. Sampling methods for herbaceous species followed Goebel et al. (2003). Individuals were identified to species (or occasionally to genus or family when identification was uncertain) and percent cover was estimated using cover classes (1 = < 1%; 2 = 1-5%; 3 = 6-15%; 4 = 16-30%; 5 = 31-60%; and 6 = 61-100%). Cover classes were later converted to percent cover using the midpoint of the class range. Overall mean percent cover was computed for each experimental unit in every sampling period. In addition, the herbaceous layer was separated into functional groups (i.e., forbs, graminoids, ferns, horsetails & lycopods, and mosses) and mean cover of each group was computed for each experimental unit in every sampling period. To assess if herb abundance changed differently in plots close to the stream edge and plots close to the clearcut edge, cover of the entire herbaceous layer was further summarized for the subset of plots that were located (1) within 10 m of the stream and (2) within 10 m of the clearcut edge.

Data Analysis

To examine species composition changes from pre- to post-treatment sampling periods, multivariate analyses were performed on stand-level abundance averages (woody regeneration: density (stems ha^{-1}); herbaceous layer: percent cover) for each species in every experimental unit (n = 12) by time period (n = 4 [pre-treatment and one, three, and nine years post-treatment] for both woody regeneration layers and n= 3 [pre-treatment, one and nine years post-treatment] for the herbaceous layer). Species with fewer than 3 occurrences were omitted from all data sets; in addition the ‘unknown’ species categories that were not uniformly used throughout the study period ('forb', 'fern', 'grass', and 'unknown') were omitted. Therefore, 23, 24, and 76 species remained in the large regeneration layer, small regeneration layer, and herbaceous layer datasets, respectively.

Permutation-based MANOVA (PerMANOVA), Indicator Species Analysis, and Nonmetric Multidimensional Scaling (NMS) analyses were conducted using PC-Ord 5.0 (McCune & Mefford 1999). PerMANOVA analysis evaluated the differences in species between groups based on a two-way factorial with treatment, time, and their interaction as factors. The Sorensen (Bray-Curtis) distance measure was used (Sorensen 1948) and 4999 randomizations were run for the randomization test of significance of pseudo F-values. Model factors were considered significant if the p-value was less than 0.10. Indicator Species Analysis was used to determine which species, if any, was indicative of a particular treatment*time combination. A species was considered a significant indicator if the Monte Carlo test for significance resulted in a p-value less than 0.10 and the indicator value for that species in given treatment*time was at least 20 units greater than in other treatment*time combination.

To evaluate the similarity of each vegetation layer in response to riparian management treatments through time, an NMS using the Sorensen (Bray-Curtis) distance measure (Sorensen 1948) was run for each vegetation layer with 50 runs of the real data along with 250 runs with randomized data for a Monte Carlo test of significance. For all vegetation layers, Pearson Correlations (r values) were calculated for each species in the main matrix and each quantitative variable in the secondary matrix with the axes found by the NMS. For large and small woody regeneration, time was the only quantitative variable in the secondary matrix (overstory basal area and density and sapling density were not measured every year and therefore could not be used in the secondary matrix). For the herbaceous layer, time, overstory basal area and density, and sapling density were in the secondary matrix. Only species and environmental variables of the secondary matrix with correlations greater than 0.40 are shown in overlays and interpreted. To help with interpretation, synecological light coordinates (1 = extremely shade tolerant to 5 = extremely shade intolerant) (Bakuzis and Kurmis 1978) of each indicator species were obtained and notes on habitat from USDA (2008), Barnes and Wagner (1981), and Voss (1985, 1996) were recorded. Analyses were done with untransformed data (large regeneration layer), log-transformed data (small regeneration layer) and relativized by the maximum mean cover value per species (herbaceous layer).

To evaluate the amount of vegetation change in each treatment unit over time, NMS scores were used to calculate the vector lengths, or average distance moved, for each treatment unit at successive time periods. For the woody regeneration layers, 4 average vector lengths per treatment were calculated (distance from (1) pre-treatment to year one; (2) year one to three; (3) year three to nine, and (4) year nine to pre-treatment). For the herbaceous layer, only three average vector lengths were calculated for each treatment (distances from (1) pre-treatment to year one; (2) from year one to nine; and (3) from year nine to pre-treatment). For each layer, a univariate one-way ANOVA was used to analyze if overall vegetation change (the vector lengths) between each time period was different among the treatments. Under a Protected least significant difference (Protected LSD) of the overall model for each distance and vegetation layer, pre-determined contrasts were constructed to compare treatments in the following ways: (1) Full Control vs. Riparian Control for the effect of a clearcut edge in unharvested

RMZs; (2) CTL vs. TL for comparing harvesting methods; and (3) Riparian Control vs. partially cut RMZs for comparing the effect of partial harvests in RMZs, and (4) Full Control vs. partially cut RMZs (averaged CTL and TL) for testing the combined effects of the clearcut edge and partial harvest in the RMZ. The hypothesis testing for these multiple comparisons were controlled using the Bonferroni method with an overall $\alpha = 0.10$ (thus individual hypothesis tests were evaluated at $\alpha_i = 0.10/4 = 0.025$).

A repeated two-way mixed ANOVA model was used to test if average cover of herbaceous species was affected by treatment, time, and the treatment*time interaction. The repeated and random statements for all tests were time and unit nested in treatment, respectively. Several covariance structures appropriate for unequal lengths of time between sampling periods (i.e., one year, three years, and nine years post-treatment) were examined and the structure with the lowest Akaike Information Criterion (AIC) value was chosen for the analysis. Degrees of freedom were calculated using the Satterthwaite method (Satterthwaite 1946), which is the preferred method for calculating degrees of freedom when tests and contrasts are a linear combination of mean squares (Littell et al. 1996; Oehlert 2000; Casler 2006). Under a Protected LSD, a subset of pairwise comparisons of differences of least squared means were examined to directly answer the following pre-determined questions: (1) How does a particular treatment change over time; and (2) Are treatments different within a particular time period. A Bonferroni correction was used to assess time and treatment differences at the overall α=0.10 level. For herbaceous cover, α_i was set at 0.025 ($\alpha_i = 0.10/4$) for time comparisons within treatment levels and at 0.0083 ($\alpha_i = 0.10/12$) for treatment comparisons within each level of time. All univariate analyses were performed in SAS 9.1 (SAS Institute).

RESULTS

Ordination of the large regeneration layer

PerMANOVA analysis revealed that the species composition in the large regeneration layer was significantly different among treatment*time combinations ($F_{9,32} = 1.5$, $p = 0.022$). Indicator analysis identified the species in the large regeneration layer that were indicators for a particular treatment*time combination (Table 2). Almost all of the significant species at years three and nine post-treatment were indicators for the CTL and TL treatments; in year nine, some of these indicators were also abundant in Riparian Controls. Further, indicator species were mostly tolerant shrubs or intolerant tree species. There were no indicator species for the Full Controls at any time period.

NMS found a three-dimensional solution for the large regeneration layer (final stress of 10.7; Monte Carlo test, $p = 0.004$), accounting for 85.6% of the total variation (Axis 1 explained 47%, Axis 2 = 29%, and Axis 3 = 10%). The two strongest axes (Axes 1 and 2) are represented in Figure 1. The Full Control replicates were tightly clustered, regardless of time periods sampled. Pre-treatment Riparian Control, TL, and CTL replicates were interspersed with these Full Control clusters. With few exceptions, Riparian Controls stayed in the vicinity of the Full Control cluster until year three and moved closer to the partially harvested replicates in year nine. In contrast, the two partially harvested treatment replicates were clustered in the opposite ordination space from the Full Controls as early as year one after harvest and were tightly clustered in both years three and nine. Aspen was strongly correlated with Axis 2 ($r = 0.818$) and many of the reported indicator species had strong correlations with Axis 1 (Table 3).

In terms of species composition, the NMS showed that aspen strongly defined the CTL and TL treatments in year three, whereas honeysuckle (*Lonicera* spp. = *L. canadensis* Marshall and *L. villosa* Michx.), raspberry (*Rubus* spp. = *R. idaeus* L. ssp. *strigosus* (Michx) Focke and *R. allegheniensis* Porter) and willow (*Salix* spp.) dominated these treatments in year nine. In years three and nine, mountain maple (*Acer spicatum* Lam.), hazel (*Corylus* spp. = *C. cornuta* Marsh. and *C. americana* Walter), red elderberry (*Sambucus pubens* Michx.*)*, red maple (*Acer rubrum* L.), and paper birch were the main components of the partially harvested treatments. Interestingly, sugar maple was important in the Full Controls in every sampling period and in the partially harvested treatments in year nine and somewhat in year three. American elm (*Ulmus Americana* L.*)* had a similar pattern to that of sugar maple but was not important in year three of the CTL and TL treatments. Black ash was abundant in year nine in the partially harvested treatments and Riparian Controls in year nine.

There were significant differences in the amount of vegetation change (reflected by vector lengths in the ordination space) among treatments between pre-treatment to nine years post-treatment (cumulative change, $F_{3,8} = 8.6$, $p = 0.007$), between pre-treatment and year 1 ($F_{3,8} = 9.4$, $p = 0.005$), between years one and three ($F_{3,8} = 6.7$, $p = 0.015$), but not between years three and nine ($F_{3,8} = 2.3$, $p = 0.153$). Full Controls showed significantly less cumulative change than Riparian Controls ($p = 0.015$), although amounts of change were not significantly different when investigated for each time period separately (i.e., changes between pre-harvest to year one ($p = 0.705$), between years one to three ($p = 0.304$), and between years three to nine ($p = 0.074$)). Amounts of vegetation change were not significantly different between the CTL and TL treatments between pre-treatment and year one ($p = 0.060$), years one to three ($p = 0.033$), and years three to nine ($p = 0.483$), or cumulatively between pre-treatment and year nine ($p = 0.344$). Riparian Controls and partial cuts did not show significantly different amounts of vegetation changes either cumulatively ($p = 0.205$) or between years one and three ($p = 0.062$) and years three to nine ($p = 0.989$). However, Riparian Controls showed significantly less change than partially cut RMZ treatments from pre-treatment to year one ($p = 0.003$). Lastly, cumulative changes were significantly greater for the partially harvested RMZ treatments compared to the Full Controls ($p = 0.001$). This was also observed between pre-treatment and year one ($p = 0.006$), years one and three ($p = 0.009$), but not between years three and nine ($p = 0.044$).

Ordination of the small regeneration layer

PerMANOVA analysis showed that the species composition in the small regeneration layer was significantly different among treatments ($F_{3,32} = 5.8$, $p < 0.001$) and time periods ($F_{3,32} = 4.9$, $p < 0.001$); the treatment*time interaction was not significant ($F_{9,32} = 0.75$, $p = 0.92$). Only three species of the small regeneration layer were identified by Indicator Species Analysis to be different among treatments (Table 2). Aspen was an important indicator for the partially harvested treatments in year one, raspberry was for the same treatments in year nine, and white spruce (*Picea glauca* (Monech) Voss) was for Riparian Controls in year nine.

NMS found a two-dimensional solution for the small regeneration layer (final stress of 20.7; Monte Carlo test, $p = 0.012$), accounting for 74.3% of the total variation (Axis 1 = 37% and Axis 2 = 37.3%) (Figure 2). Full Control replicates were tightly clustered throughout time. The clustering of the CTL and TL treatments at each time period was weak. However, CTL and TL replicates were clustered in the upper half of Axis 2 in year one and in the lower half of Axis 2 in years three and nine when they covered almost the entire range of Axis 1. The Riparian Control replicates occupied the center of the ordination space and covered the opposite end of Axis 1 from the Full Controls. Abundance of sugar maple was strongly negatively correlated with Axis 1 ($r = -0.904$) and sustained reductions in abundance over time in most treatment replicates other than the Full Controls. In contrast, abundances of aspen ($r = 0.772$) and red maple ($r = 0.559$) were strongly positively correlated and abundances of raspberry ($r = -0.463$) were negatively correlated with Axis 2. All correlations between species in the small regeneration layer and the NMS axes are shown in Table 4.

There were significant differences among treatments in the cumulative amount of vegetation change in the small regeneration layer from pre-treatment to nine years post-treatment ($F_{3,8} = 11.9$, $p = 0.003$); however, differences among treatments between pre-treatment to year one post-treatment ($F_{3,8} = 1.4$, $p = 0.30$), from year one to three ($F_{3,8} = 3.3$, $p = 0.081$), and from year three to nine ($F_{3,8} = 0.8$, $p = 0.52$) were not statistically significant. The cumulative amount of change in the Full Controls was not significantly different from that in the Riparian Controls ($p = 0.078$); however, cumulative change in Riparian Controls was significantly less than in the partial cuts ($p = 0.010$). Further, cumulative change in Full Controls was significantly less than in the partially harvested RMZ treatments ($p = 0.001$). The cumulative amount of change in the TL and CTL treatments was similar to one another ($p = 0.34$).

Ordination of the herbaceous community

PerMANOVA analysis showed that the species composition in the herbaceous layer was significantly different among treatments ($F_{3,24}$ = 1.8, p = 0.001) and time periods ($F_{2,24}$ = 2.1, p = 0.002); the treatment*time interaction was not significant ($F_{6,24}$ = 0.5, p = 1.00). Indicator analysis identified the species in the herbaceous layer that were indicators for a particular treatment*time combination (Table 2). Round-lobed hepatica (*Hepatica americana* (DC.) Ker Gawl.) was the only indicator species for the Full Control treatment at all sampling periods. The other indicator species were strongly associated with the partially harvested treatments in year nine post-treatment. The majority of these species are exotic, found in disturbed areas, or both.

NMS found a three-dimensional solution for the herbaceous layer (final stress of 14.8; Monte Carlo test, p =0.004), accounting for 75.5% of the total variation in the data set (Axis 1 = 34.2%, Axis 2 = 26.5%, and Axis 3 = 14.8%). Axes 1 and 2, the strongest axes are represented in Figure 3. Full Control replicates were weakly clustered though time in the ordination space and were mostly associated with intermediate to upper positions along Axis 2. In contrast, Riparian Control, CTL, and TL treatment replicates occupied intermediate to lower positions along Axes 1 and 2 in years one and nine. Overstory basal area (Axis 1: r = 0.239; Axis 2: r = 0.450), overstory density (Axis 1: r = 0.247; Axis 2: r = 0.279), and sapling density (Axis 1: r = -0.203; Axis 2: r = -0.250) were only moderately to weakly correlated with Axis 1 and 2.

In terms of species composition and abundance, the NMS showed that round-lobed hepatica (*Hepatica americana* (DC.) Ker Gawl.) was highly associated with the Full Control treatment at every sampling period. The species that were most abundant in the partially harvested treatments at year nine include: Canadian anemone (*Anenome canadensis* L.), spotted water hemlock (*Cicuta maculata* L.), thistle (*Cirsium* spp.), wild strawberry (*Fragaria virginiana* Duchesne), naked miterwort (*Mitella nuda* L.), northern sweet coltsfoot (*Petasites hybridus* (L.) G. Gaertn. B. Mey. & Scherb.), and common dandelion (*Taraxacum officinale* F.H. Wigg.). Additionally, large-leaved aster (*Aster macrophyllus* L.), ostrich fern (*Matteuccia struthiopteris* L. Todaro), and dwarf red raspberry (*Rubus pubescens* Raf.) were abundant in the partially harvested treatments and Riparian Control treatment at year nine. Most of the herbaceous species, however, were not particular to any one or two treatment*time combinations. These species include: wood anemone (*Anemone quinquefolia* L.), spikenard (*Aralia* spp. = *A. racemosa* L. and *A. nudicaulis* L.), jack-in-the-pulpit (*Arisaema triphyllum* (L.) Schott), wild ginger (*Asarum canadense* L.), blue beadlily (*Clintonia borealis* (Aiton) Raf.), bladderfern (*Cystopteris* spp. = *C. bulbifera* (L.) Bernh and *C. fragilis* (L.) Bernh), horsetail (*Equisetum* spp. = *E. arvense* L., *E. fluviatile* L., *E. hymale* L., *E. pretense* Ehrh., *E. sylvaticum* L., *E. scirpoides* Michx.), western oakfern (*Gymoncarpium dryopteris* (L.) Newman), pea (*Lathyrus* spp. = *L. ochroleucus* L. and *L. palustris* L.), Canada mayflower (*Maiathemum canadense* Desf.), moss, sensitive fern (*Onoclea sensibilis* L.), rough ricegrass (*Oryzopsis asperifolia* Michx.), Clayton’s sweetroot (*Osmorhiza claytonia* L.), twisted stalk (*Streptopus roseus* Michx.), starflower (*Trientalis borealis* Raf.), perfoliate bellwort (*Uvularia perfoliata* L.), sessile bellwort (*Uvularia sessilifolia* L.), and smooth Solomon’s seal (*Polygonatum biflorum* (Walter) Elliot). All correlations between herbaceous species and NMS axes are in Table 5.

There were significant cumulative differences among treatments in the composition of the herbaceous community from pre-treatment to nine years post-treatment ($F_{3,8} = 6.7$, $p = 0.015$). Whereas cumulative changes were significantly smaller in Full Controls than in partially harvested treatments ($p = 0.003$), they were not significantly different between Full Controls and Riparian Controls ($p = 0.058$), CTL and TL treatments ($p = 0.122$), and Riparian Controls and partially harvested treatments ($p = 0.157$). There were no treatment differences in herbaceous community changes from pre-treatment to one year post-treatment ($F_{3,8} = 0.9$, $p = 0.48$), but there were significant treatment differences between years one to nine ($F_{3,8} = 5.8$, $p = 0.021$). Again, changes were significantly smaller in Full Controls than in partially harvested treatments ($p = 0.004$), but not significantly different between Full Controls and Riparian Controls ($p = 0.19$), CTL and TL treatments ($p = 0.46$), and Riparian Controls and partially harvested treatments ($p = 0.051$).

Percent cover change of the herbaceous community

There were no pre-treatment differences in average herbaceous cover at the stand level ($F_{3,8} = 1.22$, $p = 0.3643$). However, herbaceous cover at the stand level increased significantly from year one to nine post-treatment (time: $F_{1,8} = 42.0$, $p < 0.001$), but the increase was not different among the treatments (treatment: $F_{3,8} = 1.1$, $p = 0.39$; treatment*time: $F_{3,8} = 2.1$, $p = 0.18$) (Figure 4). Although average cover of most functional groups also increased over time in the Riparian Control, CTL, and TL treatments (Table 6), few significant differences were found. Ferns ($p = 0.088$) and horsetails/lycopods ($p = 0.100$) had marginally significant treatment*time terms, but none of the treatment*time pairwise comparisons were significant at the Bonferroni adjusted alpha values. Average forb cover ($p = 0.35$), graminoid cover ($p = 0.81$), and moss cover ($p = 0.74$) did not show a significant treatment*time interactions. Further, no significant differences in changes of average percent cover by treatment were found in plots that were within 10 m from the stream (treatment*time: $F_{3,8} = 2.0$, $p = 0.20$; Figure 5a) or within 10 m from the clear-cut edge (treatment*time: $F_{3,8} = 2.4$, $p = 0.15$; Figure 5b). For both categories, Time was a significant factor in the model (stream: $F_{1,8} = 34.76$, $p < 0.001$; clearcut: $F_{1,8} = 16.48$, $p = 0.004$), however, Treatment was not significant (stream: $F_{3,8} = 1.17$, $p = 0.38$; clearcut: $F_{3,8} = 0.44$, $p = 0.73$).

DISCUSSION

Overall, it is difficult to assess to what extent the understory plant community has changed and how the Riparian Controls compare to the partially harvested treatments. With the exception of the large regeneration layer, I did not find the great differences between the non-harvested and harvested riparian buffers that were anticipated. In particular, the small regeneration layer and herbaceous plant community results are somewhat mixed.

The overall change in community composition and abundance (as indicated by the distance moved in ordination space) of the large regeneration layer was generally significantly different between the Full Controls and partially harvested RMZ treatments. There were few differences between the Riparian Controls and the Full Controls and the Riparian Controls and partially harvested RMZ treatments. Also, the greatest change in the large regeneration layer occurred early on, as vector length between years three and nine was not significantly different among treatments. Although the vegetation in the small regeneration layer showed significant cumulative changes in community structure, with changes in the partially harvested treatments exceeding those in the Full Controls and Riparian Controls, few significant changes were found between successive sampling periods. One exception, however, was the significantly greater change observed in partially harvested treatments compared to the Full Controls between years one and three that wsas due to the drastic change in aspen (i.e., advancement of aspen to taller forest strata and aspen mortality, see Chapter 1). Lastly, there were no significant differences in average herbaceous cover among treatment*time combinations, although the cumulative change of the herbaceous community over the sampling period was statistically significant. Again, this was due to differential amounts of change between the partially harvested treatments and the Full Controls, which is a recurring outcome in all sampled vegetation layers.

Contrary to the lack of significant differences in the analyses, field observations support change in structure and composition over time and treatment, albeit antidotal. Visually, the structure and plant abundance of the harvested RMZ units compared to the Control units was quite different with the harvested RMZs having greater abundances of herbaceous plants, shrubs, and regenerating trees with far fewer overstory trees in the canopy compared to the Controls. The Riparian Control units, by field observation, looked intermediate to the harvested RMZs and Control units. Side lighting from the harsh edge left from clearcut upland and loss of trees near the cut edge from blowdown likely contributed to the intermediate appearance of the RMZ Control units. Secondly, field observations suggest that the light from the clearcut edges adjacent to the RMZ

Control, CTL, and TL units was not uniformly distributed throughout the RMZ of each unit. The appearance of the structure, composition, and species abundance in the harvested RMZ units within 10 m of the stream edge and 10 m from the clearcut edge were quite different in most cases. By design, the gradient of overstory removal likely explains this difference, as there was greater residual basal area near to the stream compared to the clearcut edge.

There is strong evidence indicating that the large regeneration plant community in the cut RMZs has changed dramatically in species composition and abundance over the duration of the study. This is especially true of the intolerant species such as aspen and paper birch, which were both important components of the partially cut RMZ in the ordination and were indicators of these treatments. This result is in keeping with findings by other studies that have noted that increasing harvesting intensity leads to greater abundances of shade-intolerant understory species in managed forests (e.g., Fredericksen et al. 1999; Battles et al. 2001). Presumably, this is due to greater light availability in managed stands (Scheller and Mladenoff 2002). Although I generally found differences in plant community composition and abundance of woody species in the large regeneration layer between Full Controls and Riparian Controls to the partially harvested treatments, treatment differences for the small woody regeneration and herbaceous plants were generally restricted to Full Controls and partially harvested treatments.

Although the PerMANOVA and vector lengths of the small regeneration layer and herbaceous layer were not significant, the averaged ordinations for these two layers showed some distinctions among treatment*time combinations. In these two layers, the Full Control treatments at all time periods were well-clustered, whereas the pre-treatment

CTL, TL, and Riparian Controls were not tightly clustered through time, showing that there is some variation in species composition and abundance among treatments prior to treatment. However, important patterns do exist through time that separate treatments in the small regeneration layer and less so for the herbaceous layer. For instance, the small regeneration layer ordination distinctly shows that aspen is important at year one post-treatment. Further, in this layer, there were weak treatment*time groupings for the CTL and TL treatments (Figure 3).

In the herbaceous layer, the NMS showed no distinct treatment*time groupings (Figure 5) and there were only slight to moderate correlations with each axis and overstory basal area and density and sapling density. This may be due to an abundance of generalist species that did not respond to the harvest gradient created in this study. There were, however, a few indicator species of disturbance and high-light and disturbed conditions (e.g., dandelion, wild strawberry, thistle, and asters) in the Riparian Controls and particularly in the TL and CTL treatments in year nine. This indicates that there was a certain amount of change in response to the harvest, but that the change was too limited to be statistically significant, especially when these results are coupled with the lack of significance in herbaceous cover in treatment*time.

There are several reasons that would explain why I did not detect drastic changes in composition and abundance in the herbaceous community layer. One possible explanation is that the sampling window might have missed the change and subsequent recovery of the herbaceous layer as there were eight years between post-harvest sampling periods. For example, Jenkins and Parker (2000) found very little difference in the herbaceous plant community between a clearcut, group-selection openings, and single-tree selection openings compared to 80-100 year reference stands in stream bottomland forests in southern Indiana. They concluded that majority of their managed stands were >10 years old and had already undergone canopy closure, which may have allowed light and moisture conditions to return to reference forest conditions which dictate the herbaceous plant community. Further, Kern et al. (2006) failed to detect differences in understory plant community composition and abundance in three uneven-aged management silvicultural prescriptions on a gradient of harvesting intensity. They posed the possibility of plant community change and recovery within the nine years since last entry in their study. In terms of this study, if change and recovery indeed occurred within less than a decade, then it is possible that change in composition and abundance of the herbaceous layer in this study might have been missed.

A more likely alternative is that significant changes in plant composition and abundance never occurred in response to harvest because the treatments were not intense enough to induce widespread change in plant community composition and abundance. For example, Zenner et al. (2006) found that understory trees, shrubs, and some herbaceous plant forms significantly increased in abundance four years after harvest only in the two most intense treatments (group selection and clearcutting) and not in less intense treatments (single tree selection and thinning) in mixed oak forests in Missouri. They concluded that understory vegetation responded to a gradient of harvesting intensities, but that the level of harvesting intensity may have to first surpass a threshold of the plant groups for change to occur. Similarly, Macdonald and Fenniak (2007) found a threshold between 20% and 75% retention harvesting in different types of boreal forests in Canada. The authors found that plant communities change with increasing intensity of partial harvesting but that explicit changes in species indicators for shade tolerance occurred in the greater tree retention treatments two years post-harvest. Further, Halpern et al. (2005) found a strong difference in magnitude of plant community compositional change between 15% and 40% retention in western Oregon and Washington one to two years post-harvest. Yet another study, comparing partially harvested to uncut western hemlock-Sitka spruce forests in southeast Alaska found that overall, the understory plant community was not different between treatments (Deal 2001). However, after separating the partially harvested stands based on low (1-25% BA), medium (26-50% BA), and heavy (>50% BA) harvesting intensity, the author found that the heaviest cutting intensity did change the plant composition and abundance from pre-treatment conditions.

In addition to insufficient overstory tree removal, lack of soil disturbance is another reason why the treatments may not have caused highly significant changes in the small regeneration and herbaceous plant communities. For this study, it was reported that the CTL and TL treatments had greater exposed mineral and organic soil than the Riparian Control (Mattson & Thompson 1998). Further, the TL treatment had more soil exposed than the CTL due to greater travel of skidders through the site. However, these differences may not be great enough to have caused wide species compositional changes through time. Hughes and Fahey (1991) found that where almost a third of the forest floor was left undisturbed after harvest, the species composition of herbs and shrubs in the understory were similar to pre-harvest conditions. The authors concluded that canopy disturbance did not necessarily lead to understory plant changes if some proportion of the soil were left intact. Plants established before the canopy disturbance responded vegetatively to the overstory openings and new species only arose when patches of established plants were disturbed via forest floor disturbance. Hence, plant communities might exhibit a certain degree of resistance to change after timber harvesting regardless of treatment intensity.

It further appears that harvest intensity thresholds may also be specific to different ecosystems and plant species. For example, I did not see significant herbaceous plant community changes even though both initial cutting intensity and additional decreases in stand basal area over time as a result of blowdown (see Chapter 1) in the partially harvested RMZ treatments resulted in lower basal areas than what was reported for the group selection treatment in Missouri, which did exhibit significant changes (Zenner et al. 2006). In contrast, the most dramatic differences in both woody layers occurred at year one (small regeneration layer) and three post-treatment (large regeneration layer) in our partially harvested treatments, when residual basal area was likely not as low as year nine. In fact, treatment*time clusters in the NMS ordination space for each plant community layer became less distinct from large regeneration layer to small regeneration layer to herbaceous layer. The herbaceous layer had the weakest response to treatment compared to the two woody regeneration layers.

General trends aside, the partially harvested RMZ treatments had greater abundances of disturbance-indicating plants in the large regeneration layer and the herbaceous layer. Hazelnut, mountain maple, and raspberry increased in importance in the partially cut treatments over time as shown in the large regeneration ordination. These species are well known for increasing in abundance after overstory canopy and/or soil disturbance resulting from harvesting (Metzger and Schultz 1984; Hughes and Fahey 1991; Roberts and Gilliam 1995; Mallik et al. 1997; Archambault et al. 1998; Harvey and

Brais 2002; Berger et al. 2004; Royo and Carson 2006). Further, these species and other light demanding species in all layers were indicators for the partially harvested treatments and were less so for the Full Control or Riparian Control treatments. Additionally, the herbaceous layer of the partially cut stands had several species that are known as shade intolerant, disturbance species and introduced species, which can result from timber harvesting (Metzger and Schultz 1984; Battles et al. 2001; Buckley et al. 2003; Zenner et al. 2006). This shows that the CTL and TL treatments have shifted, albeit slightly, the understory plant community composition to shade intolerant species. These disturbance indicators, woody and herbaceous, will likely decline with time with canopy closure (Metzger and Schultz 1984; Archambault 1998).

MANAGEMENT IMPLICATIONS & CONCLUSION

The partial harvests seem to create a variable light and disturbed soil environment where intolerant trees, like aspen, paper birch, and native shrubs, like raspberry and hazelnut increase in abundance, especially in the large regeneration layer. Herbaceous plant composition was not different by treatment and time interaction but there may be some trends of increasing cover in the partially harvested treatments through time. It seems that the herbaceous community is not changing in composition but increasing in abundance where there is more light availability due to the overstory basal area removal.

As expected, disturbance indicating species are present, and the woody indicators seem to be on the rise in the partially harvested treatments. However, I also expect these abundances to diminish with canopy closure. It is important to note that these species are typical of northern hardwood forests and are mostly native. There were few introduced species found in the CTL and TL treatments. Additionally, increases in tree species density are only present in the partially harvested stands. The previously dominant intolerant tree species are advancing out of the understory and tolerant tree species, like sugar maple, are now an important component of the woody understory (Chapter 1).

Overall this study has shown that as of nine years post-treatment, partial harvests in the RMZs were not intense enough disturbances to greatly alter understory plant communities. Given the results of this study, partial overstory harvests in riparian areas create open canopy conditions for tree regeneration and provide for increased abundance of native shrubs and herbaceous plants, most of which are found in non-harvested Riparian Management Zones. Continued research is needed to fully understand the long term implications of forest management in riparian areas, however, in comparison to Riparian Controls, partial harvesting in riparian areas may be a good management approach in these ecosystem types in terms of balancing traditional forestry objectives and maintaining the understory plant community.

Table 1: Summary of live overstory (≥ 10 cm DBH) and sapling (2.5 – 9.9 cm DBH) trees by treatment over time. Standard errors are noted in parentheses.

Time	**Full Control**	**Rip. Control**	**Cut-to-length**	**Tree Length**
	Overstory Density (stems/ha)			
Pre-treatment	636.5 (135.6)	734.2 (135.6)	608.5 (135.6)	735.4 (135.6)
1 yr post-treatment	NA	NA	243.7 (57.8)	331.1 (21.6)
9 yrs post-treatment	597.8 (24.4)	507.1 (105.9)	113.6 (15.0)	163.0 (27.0)
	Overstory Basal Area (m^2/ha)			
Pre-treatment	27.7 (4.0)	26.8 (4.0)	26.7 (4.0)	33.1 (4.0)
1 yr post-treatment	NA	NA	13.0 (2.4)	11.9 (1.0)
9 yrs post-treatment	27.9 (2.1)	20.7 (4.0)	5.6 (1.0)	5.3 (0.8)
	Sapling Density (stems/ha)			
Pre-treatment	477.6 (47.3)	348.5 (47.3)	525.8 (47.3)	480.0 (47.3)
1 yr post-treatment	NA	NA	NA	NA
9 yrs post-treatment	400.6 (142.2)	271.3 (142.2)	1045.4 (142.2)	924.2 (142.2)

Table 2. Indicator species for each vegetation layer. Light column indicates the synecological coordinate for light that the particular species represents (range from 1-5, 1 = low light environment and 5 = high light environment). Indicating group key: Control = Full Control; RC = Riparian Control; CTL = cut-to-length; and TL = tree-length.

Species	Indicating Group	Light	Shade Tolerance	Notes
Large Regeneration Layer				
Acer rubrum L.	CTL and TL yr 9	3	tolerant	
Acer spicatum Lam.	CTL yr 3, CTL and TL yr 9	1	tolerant	disturbance indicator
Betula papyrfera Marsh.	CTL and TL yr 3, CTL, TL, RC yr 9	5	intolerant	
Corylus spp.	CTL yr 9	3	tolerant	disturbance indicator
Lonicera spp.	TL yr 9			
Populus spp.	CTL and TL yr 3	3-4	intolerant	
Quercus rubra L.	CTL and TL yr 9	3	intermediate	
Rubus spp.	CTL, TL, and RC yr 9	3		Open, disturbed habitats, especially nutrient rich, moist to wet soils
Salix spp.	CTL and TL yr 9			
Ulmus americana L.	TL yr 9	2	intermediate	
Small Regeneration Layer				
Picea glauca (Moench) Voss	RC yr 9	2	intermediate	
Populus spp.	CTL and TL yr 1	3-4	intolerant	
Rubus spp.	CTL and TL yr 9	3		Open, disturbed habitats, especially nutrient rich, moist to wet soils
Herbaceous Layer				
Aster spp.	CTL yr 9			Many found in disturbed places
Caltha palustris L.	CTL yr 9	4	intolerant	Wet, open, or partly shaded sites
Cirsium spp.	CTL and TL yr 9			Many species exotic and found in disturbed places
Calystegia sepium (L.) R. Br. / *Polygonum cilinode*	TL yr 9			Found in disturbed places, especially after logging

Michx.				
Fragaria virginiana Duchesne	CTL yr 9	4		
Hepatica americana L.	Control yr 1, 3, and 9	2		Rich woods
Lycopus uniflorus Michx.	CTL yr 9	2		Found in wet places
Taraxacum officinale F.H. Wigg.	CTL and TL yr 9	5	intolerant	Exotic; found in disturbed sites

Table 3. Pearson Correlation coefficients (r value) for each species in the large regeneration layer from the NMS solution. Asterisk (*) indicates strong correlation (r ≥ 0.400).

Species	**Axis 1**	**R value** **Axis 2**	**Axis 3**
Abies balsamea (L.) Mill.	-0.274	-0.225	-0.210
Acer rubrum L.	-0.667*	0.288	-0.098
Acer saccharum Marsh.	-0.616*	0.129	-0.634*
Acer spicatum Lam.	-0.614*	0.170	0.105
Alnus rugosa (Du Roi) Spreng.	-0.212	0.260	0.174
Amelanchier sp.	-0.350	-0.202	-0.397
Betula papyrifera Marsh.	-0.675*	0.487*	-0.090
Cornus spp.+	-0.381	0.302	-0.124
Corylus spp.	-0.641*	0.326	0.092
Dirca palustris L.	-0.143	-0.366	-0.286
Fraxinus nigra Marsh.	-0.494*	0.275	0.029
Lonicera spp.	-0.486*	0.008	-0.017
Ostrya virginiana (Mill.) K. Koch	-0.409*	0.199	-0.317
Picea glauca (Moench) Voss	-0.033	-0.350	0.222
Populus spp.	-0.452*	0.818*	-0.067
Prunus virginiana L.	-0.319	0.035	0.013
Quercus rubra L.	-0.511*	-0.190	-0.127
Ribes spp.+	-0.314	0.067	-0.160
Rubus spp.	-0.571*	0.074	-0.105
Salix sp.	-0.502*	0.240	-0.108
Sambucus pubens Michx.	-0.299	0.281	-0.165
Tilia americana L.	-0.170	0.370	-0.182
Ulmus americana L.	-0.323	-0.126	-0.411*

+ *Cornus* spp. = *C. alternifolia* L. f., *C. rugosa* Lam. and *C. stolonifera* Michx.
Ribes spp. = *R. cynosbati* L., *R. glandulosum* Grauer, *R. lacustre* (Pers.) Poir., and *R. triste* Pall.

Table 4. Pearson Correlation coefficients (r value) for each species in the small regeneration layer from the NMS solution. Asterisk (*) indicates strong correlation (r ≥ 0.400).

	R value	
Species	**Axis 1**	**Axis 2**
Abies balsamea (L.) Mill.	0.273	0.269
Acer rubrum L.	0.438*	0.559*
Acer saccharum Marsh.	-0.904*	0.148
Acer spicatum Lam.	0.091	-0.38
Amelanchier sp.	0.017	0.142
Betula alleghaniensis Britton.	0.024	-0.175
Betula papyrifera Marsh.	0.095	0.059
Cornus spp.	-0.073	-0.072
Corylus spp.	0.132	-0.033
Diervilla lonicera Mill.	0.27	0.062
Dirca palustris L.	-0.156	-0.01
Fraxinus nigra Marsh.	0.466*	-0.057
Lonicera spp.	-0.203	0.262
Ostrya virginiana (Mill.) K. Koch	0.038	0.238
Picea glauca (Moench) Voss	0.272	-0.019
Populus spp.	0.076	0.772*
Prunus virginiana L.	0.273	0.055
Quercus rubra L.	-0.039	0.291
Ribes spp.	0.013	0.198
Rubus spp.	0.198	-0.463*
Salix sp.	-0.188	-0.281
Sambucus pubens Michx.	-0.013	-0.322
Tilia americana L.	-0.261	0.241
Ulmus americana L.	-0.211	0.024

Table 5. Pearson Correlation coefficients (r value) for each species in the herbaceous layer from the NMS solution. Asterisk (*) indicates strong correlation (r ≥ 0.400).

	R value		
Species	**Axis 1**	**Axis 2**	**Axis 3**
Actaea rubra Ait.	-0.193	-0.137	0.174
Adiantum pedatum L.	-0.170	-0.082	-0.465*
Amphicarpaea bracteata (L.) Fern.	-0.302	-0.555*	-0.165
Anemone Canadensis L.	-0.359	-0.389	-0.270
Anemone quinquefolia L.	-0.344	0.246	-0.031
Apocynum androsaemifolium Nutt.	-0.149	-0.073	0.216
Aralia spp.	-0.577*	-0.079	-0.224
Arisaema triphyllum (L.) Schott	-0.265	-0.139	-0.236
Asarum canadense L.	-0.584*	-0.006	-0.259
Aster macrophyllus L.	-0.349	-0.545*	-0.650*
Aster spp.	-0.407*	-0.338	-0.257
Athyrium filix-femina (L.) Roth.	-0.342	-0.544*	-0.373
Botrychium virginianum L.	-0.490*	-0.008	0.267
Brachyelytrum erectum (Schreb.) Beauv.	0.049	-0.077	0.047
Carex pensylvanica Lam.	-0.233	-0.487*	-0.167
Carex spp.	-0.452*	-0.252	-0.150
Circaea alpina L.	0.066	-0.408*	-0.364
Circaea lutetiana L.	0.372	0.290	-0.052
Cicuta maculate L.	-0.336	-0.335	-0.171
Cirsium spp.	-0.413*	-0.373	-0.200
Clintonia borealis (Aiton.) Raf.	-0.367	-0.278	-0.204
Cornus Canadensis L.	-0.289	-0.551*	-0.090
Calystegia sepium (L.) R. Br. / *Polygonum cilinode* Michx.	0.052	-0.357	-0.461*
Cystopteris spp.	-0.416*	-0.016	-0.293
Dryopteris carthusiana (Vill.) H.P. Fuchs	-0.262	-0.038	-0.270
Epilobium spp.	-0.139	-0.102	-0.064

Equisetum spp.	-0.550*	-0.471*	-0.029
Fragaria virginiana Duchesne.	-0.388	-0.366	-0.181
Galium spp.+	-0.369	-0.677*	-0.188
Gymnocarpium dryopteris (L.) Newman	-0.444*	-0.246	-0.301
Hepatica americana (DC.) Ker Gaw.	-0.405*	0.084	0.129
Impatiens capensis Meerb.	-0.305	-0.325	-0.356
Laportea canadensis (L.) Wedd.	0.592*	-0.126	-0.408*
Lathyrus spp.	-0.184	-0.263	-0.112
Liverwort spp.	-0.072	0.332	-0.028
Lycopodium dendroideum Michx.	-0.001	-0.371	-0.181
Lycopodium lucidula Michx.	0.000	-0.184	-0.335
Maianthemum canadense Desf.	-0.502*	-0.143	0.300
Matteuccia struthiopteris (L.) Todaro	-0.262	-0.502*	-0.387
Milium effusum L.	0.114	-0.221	-0.100
Mitella nuda L.	-0.316	-0.347	-0.311
Mitchella repens L.	-0.092	0.126	-0.017
Moss spp.	-0.188	-0.228	-0.461*
Onoclea sensibilis L.	-0.032	-0.576*	-0.157
Oryzopsis asperifolia Michx.	-0.396	-0.123	0.091
Osmorhiza claytonia (Michx.) C.D. Clark	-0.673*	-0.518*	0.144
Osmunda claytoniana L.	-0.280	-0.345	-0.071
Petasites hybridus L.	-0.387	-0.098	-0.319
Phegopteris connectilis (Michx.) Watt	-0.447*	-0.459*	-0.006
Polygonatum biflorum (Willd.) Pursh. /*Uvularia sessilifolia* L.	-0.492*	0.242	0.403*
Polygonatum pubescens (Walter) Elliott	-0.097	-0.030	-0.060
Pteridium aquilinum (L.) Kuhn	-0.332	-0.456*	-0.100
Pyrola spp.+	-0.508*	-0.469*	0.062
Ranunculus recurvatus Poir.	-0.151	-0.188	-0.243
Ranunculus hispidus Michx.	-0.160	-0.334	0.039

Rubus pubescens Raf.	-0.495*	-0.440*	-0.355
Sanguinaria canadensis L.	-0.259	-0.001	-0.006
Sanicula marilandica L.	-0.341	0.034	-0.058
Solidago spp.	-0.240	-0.178	-0.275
Streptopus roseus (L.) DC	-0.497*	-0.188	0.313
Taraxacum officinale F.H. Wigg.	-0.430*	-0.395	-0.325
Trientalis borealis Raf.	-0.177	0.215	-0.338
Trillium spp.	-0.161	-0.175	0.218
Tussilago farfara L.	-0.160	-0.114	-0.083
Uvularia perfoliata L.	0.002	0.453*	-0.417*
Uvularia sessilifolia L.	0.190	0.236	-0.016
Viola spp.	-0.217	-0.569*	-0.384

+*Galium* spp. = *G. asperellum* Michx. and *G. triflorum* Michx.
Pyrola spp. = *P. elliptica* Nutt. and *P. rotundifolia* L.

Table 6. Mean cover of ferns, forbs, graminoids, horsetails/lycopods, and moss in each treatment through time. Standard errors are noted in parentheses. Upper case letters indicate multiple comparisons made within the same year but among different treatments and lower case letters indicate multiple comparisons made within the same treatment among different years. Pre-treatment data were not compared to post treatment time periods.

	Full Control	**Rip Control**	**CTL**	**TL**
Time	**Fern average cover (%)**			
Pre	9.2 (4.7)^{A}	16.0 (4.7)^{A}	8.5 (4.7)^{A}	5.7 (4.7)^{A}
1 yr post	8.0 (4.4) ^{Aa}	16.5 (4.4) ^{Aa}	6.3 (4.4) ^{Aa}	5.0 (4.4) ^{Aa}
9 yrs post	4.7 (7.4) ^{Aa}	25.8 (7.4) ^{Aa}	20.2 (7.4) ^{Aa}	13.4 (7.4) ^{Aa}
	Forb average cover (%)			
Pre	22.6 (5.3) ^{A}	21.1 (5.3) ^{A}	16.3 (5.3) ^{A}	14.2 (5.3) ^{A}
1 yr post	14.8 (3.2) ^{Aa}	22.9 (3.2) ^{Aa}	15.7 (3.2) ^{Aa}	17.8 (3.2) ^{Aa}
9 yrs post	26.1 (6.8) ^{Aa}	29.9 (6.8) ^{Aa}	34.6 (6.8) ^{Aa}	41.2 (6.8) ^{Aa}
	Graminoid average cover (%)			
Pre	3.7 (1.9) ^{A}	5.0 (1.9) ^{A}	2.6 (1.9) ^{A}	2.4 (1.9) ^{A}
1 yr post	2.9 (2.1) ^{Aa}	4.7 (2.1) ^{Aa}	4.5 (2.1) ^{Aa}	5.9 (2.1) ^{Aa}
9 yrs post	5.4 (3.9) ^{Aa}	11.4 (3.9) ^{Aa}	7.7 (3.9) ^{Aa}	7.3 (3.9) ^{Aa}
	Horsetail/lycopod average cover (%)			
Pre	1.0 (0.4) ^{A}	1.2 (0.4) ^{A}	1.0 (0.4) ^{A}	0.6 (0.4) ^{A}
1 yr post	1.2 (0.7) ^{Aa}	1.4 (0.7) ^{Aa}	1.9 (0.7) ^{Aa}	0.9 (0.7) ^{Aa}
9 yrs post	1.1 (0.9) ^{Aa}	3.0 (0.9) ^{Aa}	2.3 (0.9) ^{Aa}	0.8 (0.9) ^{Aa}
	Moss average cover (%)			
Pre	2.9 (1.6) ^{A}	6.6 (1.6) ^{A}	4.4 (1.6) ^{A}	1.5 (1.6) ^{A}
1 yr post	1.8 (1.1) ^{Aa}	5.6 (1.1) ^{Aa}	3.3 (1.1) ^{Aa}	1.1 (1.1) ^{Aa}
9 yrs post	2.0 (2.2) ^{Aa}	7.8 (2.2) ^{Aa}	5.7 (2.2) ^{Aa}	3.5 (2.2) ^{Aa}

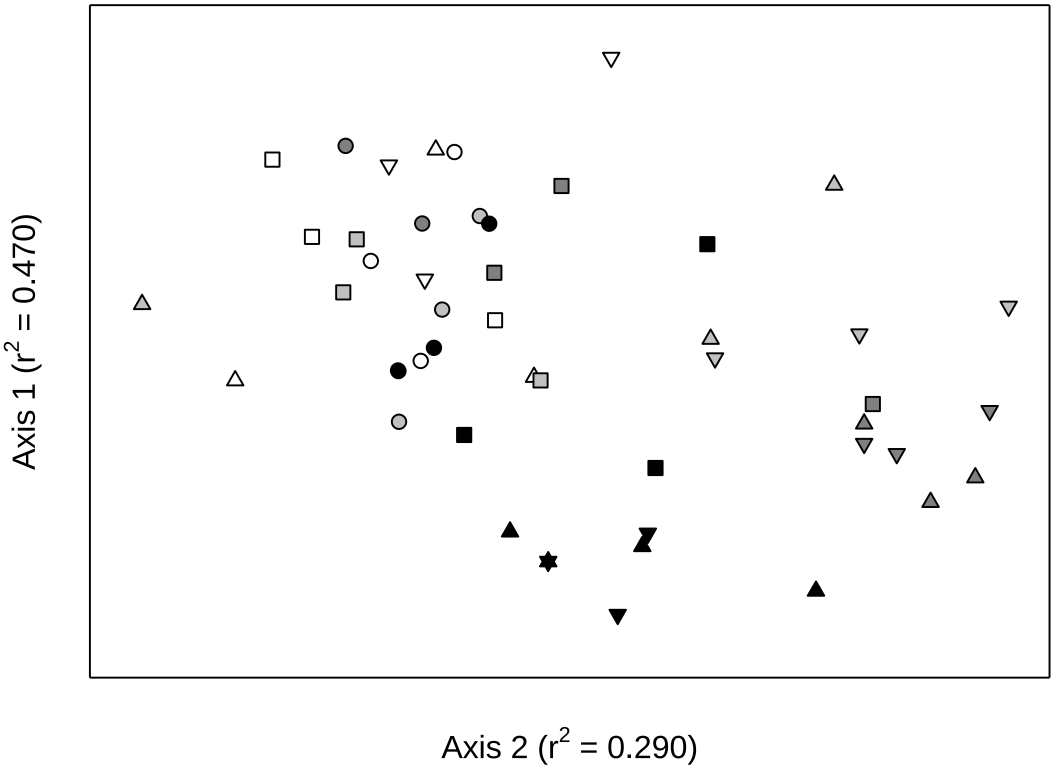

Figure 1. NMS ordination of the large regeneration layer by treatment and time. Symbol/Color combinations represent treatment*time combinations: ● = Full Control; ■ = Riparian Control; ▲ = Cut-to-length; ▼ = Tree-length; white = pre-harvest; light grey = one year post-harvest; dark grey = three years post-harvest; and black = nine years post-harvest.

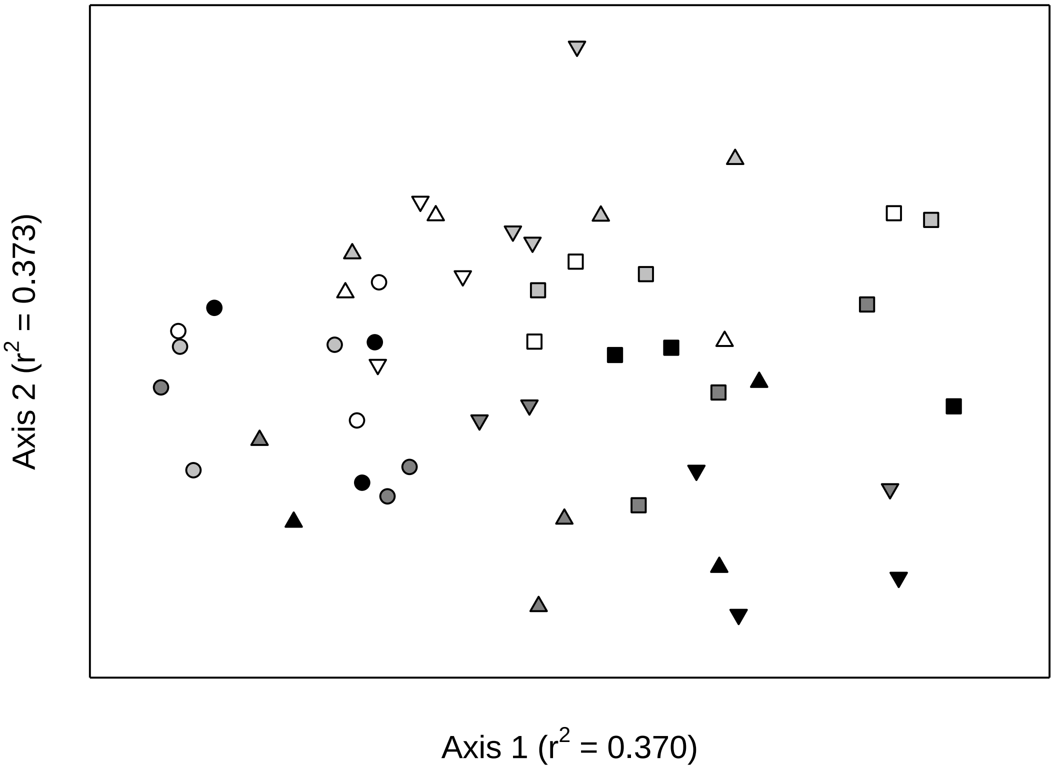

Figure 2. NMS ordination of the small regeneration layer by treatment and time. Symbol/Color combinations represent treatment*time combinations: ● = Full Control; ■ = Riparian Control; ▲ = Cut-to-length; ▼ = Tree-length; white = pre-harvest; light grey = one year post-harvest; dark grey = three years post-harvest; and black = nine years post-harvest.

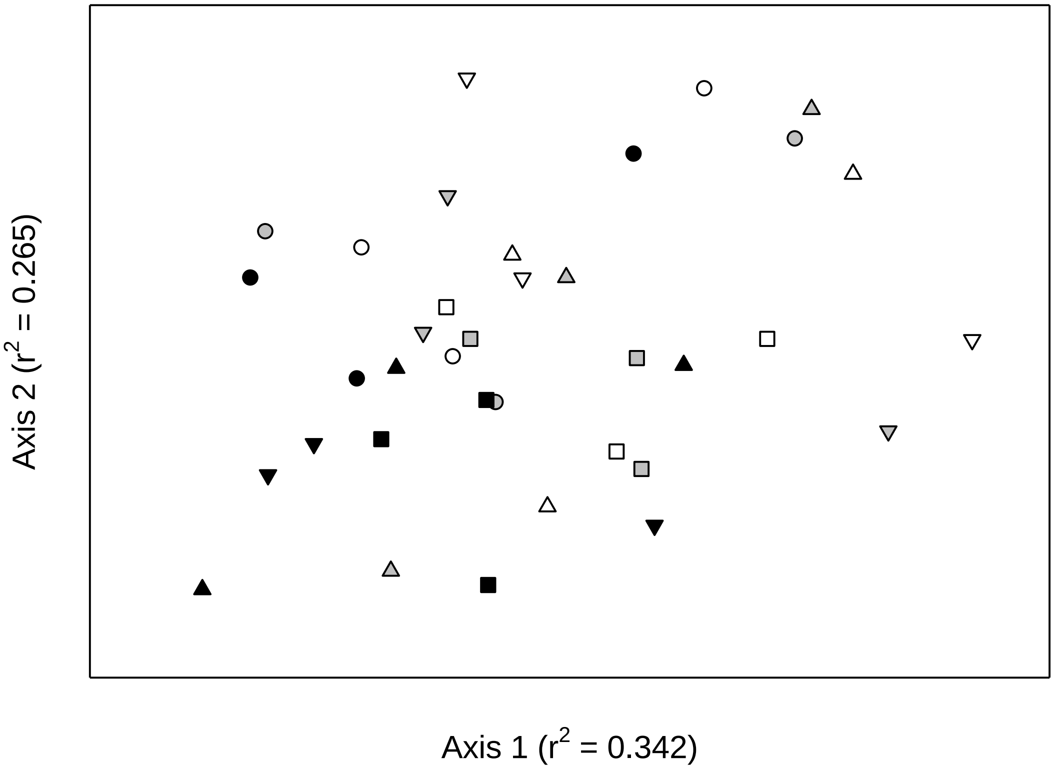

Figure 3. NMS ordination of the herbaceous layer by treatment and time. Symbol/Color combinations represent treatment*time combinations: ● = Full Control; ■ = Riparian Control; ▲ = Cut-to-length; ▼ = Tree-length; white = pre-harvest; light grey = one year post-harvest; and black = nine years post-harvest.

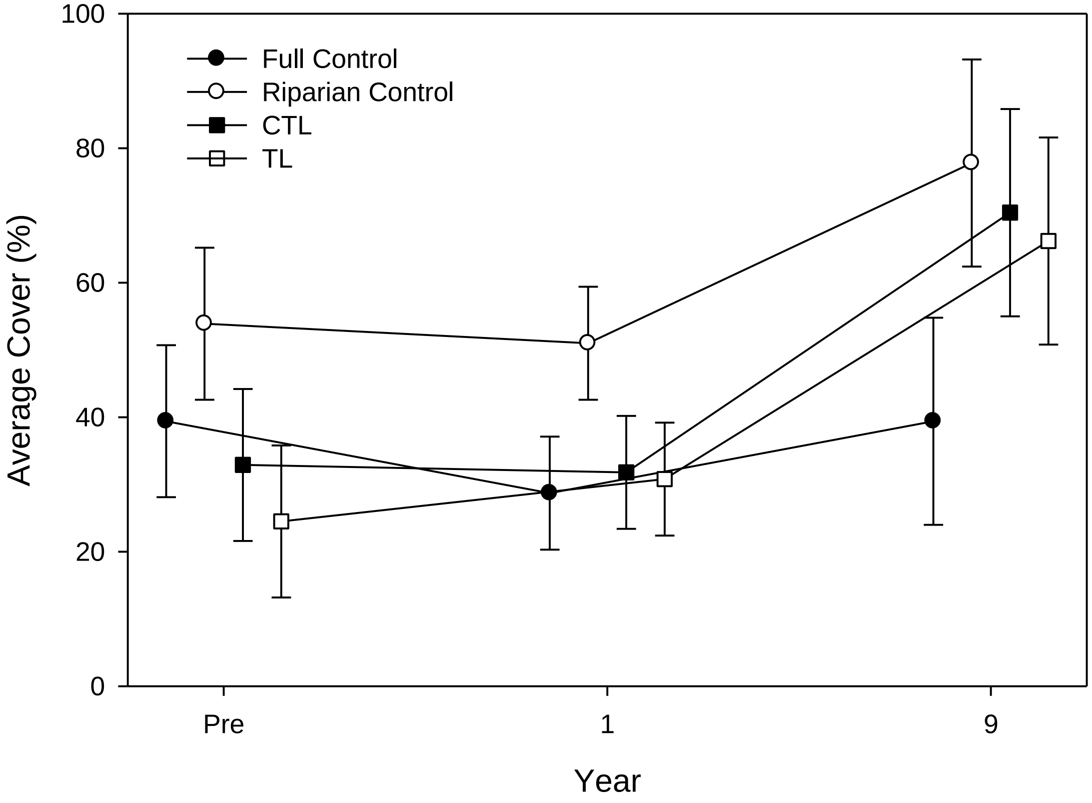

Figure 4. Average percent cover of herbaceous species over time and treatment. Error bars represent + 1 SE.

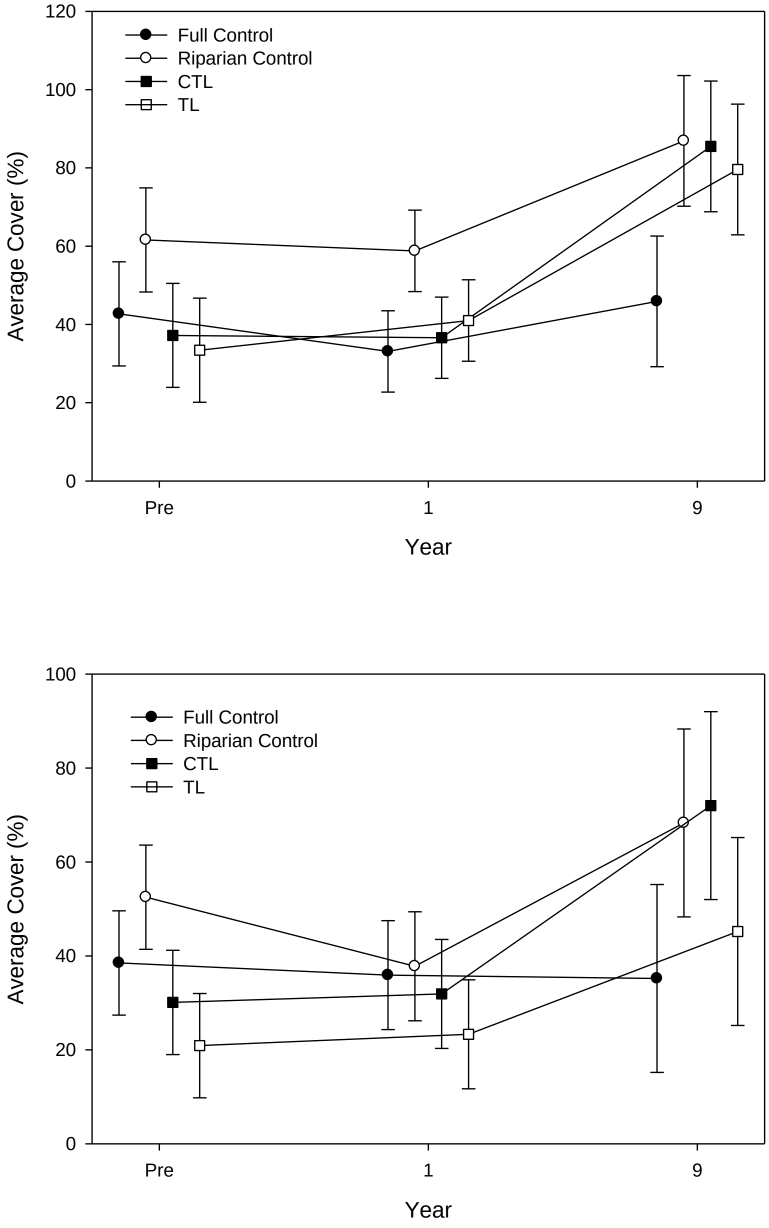

Figure 5 a,b. Average percent cover of herbaceous species over time and treatment within (a; top) 10 m from the stream and (b; bottom) 10 from the clearcut edge. Error bars represent + 1 SE.

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Appendix A. Basal area (m^2 ha^{-1}) of select species of overstory trees by treatment over time. Standard errors are noted in parentheses. NA indicates that data were not collected that year.

Time	Full Control	Rip. Control	CTL	TL
		Aspen		
Pre	6.2 (1.9)	3.4 (1.7)	5.8 (2.0)	8.0 (1.1)
1 yr post	NA	NA	2.3 (2.0)	1.4 (0.2)
9 yrs post	4.4 (1.6)	3.0 (1.6)	0.9 (0.6)	0.2 (0.1)
		Sugar maple		
Pre	6.1 (1.3)	2.2 (0.8)	3.9 (1.9)	5.6 (3.1)
1 yr post	NA	NA	1.2 (0.5)	1.9 (0.4)
9 yrs post	7.3 (1.0)	2.6 (0.5)	1.2 (0.5)	2.0 (0.6)
		Basswood		
Pre	4.2 (0.7)	0.3 (0.2)	3.5 (1.6)	1.9 (1.0)
1 yr post	NA	NA	2.2 (0.8)	1.5 (0.5)
9 yrs post	4.5 (0.9)	0.2 (0.1)	0.7 (0.4)	0.3 (0.2)
		Paper birch		
Pre	4.2 (1.7)	5.3 (1.7)	2.8 (0.7)	5.1 (1.4)
1 yr post	NA	NA	0.6 (0.1)	1.5 (0.4)
9 yrs post	4.9 (2.2)	4.5 (1.7)	0.4 (0.1)	0.3 (0.2)
		Black ash		
Pre	4.1 (1.3)	5.6 (2.1)	2.9 (1.5)	4.5 (2.0)
1 yr post	NA	NA	1.9 (0.3)	3.3 (0.7)
9 yrs post	3.8 (1.8)	4.4 (1.1)	0.5 (0.1)	1.0 (0.3)
		Balsam fir		
Pre	0.6 (0.4)	5.3 (1.7)	1.8 (0.3)	2.4 (0.9)
1 yr post	NA	NA	0.5 (0.3)	1.0 (0.3)
9 yrs post	0.4 (0.4)	2.4 (0.4)	0.1 (0.1)	0.3 (0.1)
		Other		
Pre	2.3 (1.4)	4.7 (1.2)	5.9 (1.9)	5.5 (1.5)
1 yr post	NA	NA	4.4 (1.0)	2.6 (0.6)
9 yrs post	2.6 (0.9)	3.3 (1.6)	1.8 (0.7)	1.1 (0.4)

Appendix B. Density (stems ha^{-1}) of select species of overstory trees by treatment over time. Standard errors are noted in parentheses. NA indicates that data were not collected that year.

Time	Full Control	Rip Control	CTL	TL
		Aspen		
Pre	56.5 (10.5)	42.2 (15.2)	59.7 (20.7)	78.2 (11.9)
1 yr post	NA	NA	21.5 (18.6)	18.7 (3.2)
9 yrs post	35.2 (10.2)	33.0 (21.0)	6.4 (4.3)	2.1 (1.1)
		Sugar maple		
Pre	208.7 (36.0)	108.9 (44.1)	141.0 (47.5)	207.4 (68.1)
1 yr post	NA	NA	35.8 (10.1)	82.8 (15.0)
9 yrs post	237.9 (14.2)	111.1 (24.1)	39.2 (12.2)	87.3 (26.1)
		Basswood		
Pre	89.0 (12.7)	10.8 (5.9)	65.2 (10.5)	40.7 (20.7)
1 yr post	NA	NA	44.6 (20.0)	27.7 (9.3)
9 yrs post	86.1 (13.1)	6.8 (3.9)	8.1 (3.1)	8.4 (3.6)
		Paper birch		
Pre	101.8 (45.9)	144.1 (58.7)	82.8 (21.2)	145.9 (27.3)
1 yr post	NA	NA	13.3 (0.1)	39.5 (13.7)
9 yrs post	96.2 (43.7)	102.8 (52.5)	5.2 (1.3)	7.2 (3.5)
		Black ash		
Pre	108.1 (26.5)	146.8 (41.7)	76.3 (36.4)	85.3 (17.7)
1 yr post	NA	NA	49.0 (6.8)	75.3 (9.0)
9 yrs post	80.4 (24.4)	106.8 (22.1)	14.9 (2.6)	19.8 (4.2)
		Balsam fir		
Pre	23.5 (19.4)	197.6 (43.1)	68.8 (19.3)	103.6 (33.8)
1 yr post	NA	NA	17.0 (11.6)	45.7 (14.5)
9 yrs post	16.9 (16.9)	90.3 (11.9)	7.2 (4.8)	11.4 (2.9)
		Other		
Pre	48.9 (11.7)	84.1 (20.0)	114.8 (20.2)	74.3 (17.3)
1 yr post	NA	NA	61.9 (4.6)	41.5 (2.8)
9 yrs post	45.2 (5.1)	56.2 (20.9)	33.9 (2.4)	26.8 (4.2)

Appendix C. Density (stems ha^{-1}) of select species of sapling-sized trees through time. Standard errors are noted in parentheses.

Time	**Full Control**	**Rip Control**	**CTL**	**TL**
		Aspen		
Pre	0.0 (32.4)	0.0 (32.4)	0.0 (32.4)	0.0 (32.4)
9 yrs post	1.2 (32.4)	28.6 (32.4)	273.9 (32.4)	248.9 (32.4)
		Sugar maple		
Pre	359.0 (34.9)	132.1 (36.6)	296.0 (61.7)	279.2 (81.6)
9 yrs post	302.3 (13.6)	94.1 (28.0)	184.9 (11.4)	217.7 (80.1)
		Basswood		
Pre	14.7 (6.7)	17.9 (6.7)	17.6 (6.7)	10.5 (6.7)
9 yrs post	17.4 (17.4)	13.8 (17.4)	41.8 (17.4)	36.3 (17.4)
		Paper birch		
Pre	7.9 (5.8)	23.7 (6.7)	3.8 (2.2)	17.5 (14.8)
9 yrs post	1.2 (1.2)	6.3 (3.5)	37.1 (13.4)	52.8 (21.8)
		Black ash		
Pre	6.7 (1.5)	22.7 (6.7)	38.2 (30.8)	6.9 (4.4.)
9 yrs post	0.0 (0.0)	10.4 (10.4)	32.4 (18.4)	7.0 (7.0)
		Balsam fir		
Pre	19.2 (13.4)	111.9 (11.6)	86.9 (43.3)	97.2 (41.1)
9 yrs post	17.0 (14.6)	49.2 (13.1)	139.6 (119.0)	40.1 (24.0)
		Other		
Pre	71.2 (15.5)	41.0 (12.6)	80.5 (30.0)	70.2 (35.3)
9 yrs post	61.2 (11.6)	61.0 (18.7)	190.7 (111.3)	191.6 (77.6)

Appendix D. Explanation for Bonferroni multiple comparisons method for analyzed variables.

Question 1: variable change over time in each treatment
Question 2: variable difference among treatments in each time period

Pre-harvest variable assessments for differences among treatment units
(independently analyzed from post-harvest analyses)

(Q1) not analyzed because there is no time component

(Q2) multiple comparisons made between:

Control vs. Riparian Control
Control vs. CTL
Control vs. TL
Riparian Control vs. CTL
Riparian Control vs. TL
CTL vs. TL

Therefore, α_i = 0.1/6 comparisons = 0.017

Overstory Basal Area and Density variables:

(Q1) multiple comparisons made between:
Control yrs 1 and 9
Riparian Control yrs 1 and 9
CTL yrs 1 and 9
TL yrs 1 and 9

Therefore, α_i = 0.1/4 comparisons = 0.025

(Q2) multiple comparsions made between:

Yr 1:	Yr 9:
Control vs. Riparian Control	Control vs. Riparian Control
Control vs. CTL	Control vs. CTL
Control vs. TL	Control vs. TL
Riparian Control vs. CTL	Riparian Control vs. CTL
Riparian Control vs. TL	Riparian Control vs. TL
CTL vs. TL	CTL vs. TL

Therefore, α_i = 0.1/12 comparisons = 0.008

Coarse Woody Debris and Blowdown accumulation variables:

(Q1) not analyzed because there is no time component

(Q2) multiple comparisons made between:

Control vs. Riparian Control
Control vs. CTL
Control vs. TL
Riparian Control vs. CTL
Riparian Control vs. TL
CTL vs. TL

Therefore, α_i = 0.1/6 comparisons = 0.017

Sapling density variables:

(Q1) not analyzed because there is no time component

(Q2) multiple comparisons made between:

Control yr 9 vs. Riparian Control yr 9
Control yr 9 vs. CTL yr 9
Control yr 9 vs. TL yr 9
Riparian Control yr 9 vs. CTL yr 9
Riparian Control yr 9 vs. TL yr 9
CTL yr 9 vs. TL yr 9

Therefore, α_i = 0.1/6 comparisons = 0.017

Large and Small Regeneration Layer variables:

(Q1) multiple comparisons made between:
Control yrs 1 and 3, yrs 3 and 9, and yrs 1 and 9
Riparian Control yrs 1 and 3, yrs 3 and 9, and yrs 1 and 9
CTL yrs yrs 1 and 3, yrs 3 and 9, and yrs 1 and 9
TL yrs 1 and 3, yrs 3 and 9, and yrs 1 and 9

Therefore, α_i = 0.1/12 comparisons = 0.008

(Q2) multiple comparisons made between:

Yr 1:	Yr 3:	Yr 9:
Control vs. Riparian Control	Control vs. Riparian Control	Control vs Riparian Control
Control vs. CTL	Control vs. CTL	Control vs. CTL
Control vs. TL	Control vs. TL	Control vs. TL
Riparian Control vs. CTL	Riparian Control vs. CTL	Riparian Control vs. CTL
Riparian Control vs. TL	Riparian Control vs. TL	Riparian Control vs. TL
CTL vs. TL	CTL vs. TL	CTL vs. TL

Therefore, α_i = 0.1/18 comparisons = 0.005