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Overstory and regeneration dynamics in riparian management zones of northern Minnesota forested watersheds

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ABSTRACT

We quantified tree regeneration under different riparian management zone (RMZ) treatments along first-order streams in Minnesota, USA. A primary objective for long-term management of RMZs in the study region is to maintain some tree cover and promote establishment of later successional tree species and conifers. We also compared regeneration response to contrasting harvesting systems that differed in expected soil disturbance and impact on residual vegetation. Riparian treatments included: (1) full control (no cutting in RMZ (60 m-wide in all treatments) or adjacent upland stand), (2) riparian control (RMZ uncut; adjacent upland stand clearcut); and partially-harvested RMZs (RMZ basal area reduced from 29 to 13 m^2/ha, adjacent upland stand clearcut) and using (3) cut-to-length or (4) tree-length harvesting. Nine years after treatment, basal area of the full control had not changed appreciably, while basal area of the riparian control had declined by 28% and basal area of the two partial-harvest treatments had decreased by 54%; reductions were due to blowdown of residual trees. Total regeneration density was stable over time in the full control and riparian control, but increased substantially in the two RMZ treatments. Regeneration response was driven by early successional species, mostly *Populus tremuloides* and *Betula papyrifera*, and shrubs. Responses were similar between the two harvesting systems. Our results show that regeneration does increase with partial harvesting of RMZs, that the response is mostly due to early succession, shorter-lived deciduous species, and that harvest systems that differ in expected site and vegetation impact elicit similar results. A lack of significant increases in conifers and longer-lived trees in the RMZs following treatment, and the substantial increases in shrubs which may inhibit establishment of these species, suggests a need for more active approaches to establish these species, for example through under planting and competition control.

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1. Introduction

In forested watersheds, riparian areas are important for the ecological services they provide (Gregory et al., 1991) as well as the timber resources they supply (Burns et al., 1999; Palik et al., 1999). The latter may result from the occurrence of species that are unique to riparian areas (Palik et al., 1999), but in regions rich in surface water, riparian forests are important simply because a large percentage of the timber base is close to water. For example, in Minnesota, USA at least 10% of commercial forest lies within 60 m of water (Laursen, 1996).

Ecological services of riparian forests are vulnerable to degradation by poorly designed or poorly implemented forest management practices. In theory, riparian forest management guidelines are designed to protect ecological services, while allowing for utilization of and management for timber resources. Often, the primary focus of these guidelines, which are increasingly common around the world (e.g., Lugo, 1995; Broadmeadow and Nisbet, 2004; Decker, 2003), is protection of water quality, but protection of other services, including diversity of native plants and animals and organic matter flux into the aquatic system, also may be considered. One outcome of implementing riparian management guidelines is the creation of a riparian management zone (RMZ) situated between a stream, lake, or wetland, and the (usually) more intensively managed adjacent upland forest. Typically, these guidelines specify the amount of residual overstory to retain after harvest in the RMZ, the amount of soil disturbance that is allowable (Belt and O'Laughlin, 1994; Blinn and Kilgore, 2001), and

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sometimes the species of trees that should be favored for retention, particularly for aquatic habitat and wildlife benefits.

There is extensive research on the ecological role of RMZs, including their use by birds and other wildlife (Darveau et al., 1995, 1998), their microclimatic influences (Brosofske et al., 1997), and their affects on stream habitat (Murphy et al., 1986; Quinn et al., 2004), water quality (Lowrance et al., 1984; Peterjohn and Correll, 1984), and aquatic communities (Newbold et al., 1980). Additionally, there is information on forest composition, including regeneration, in unmanaged riparian areas and uncut RMZs, especially from the mountainous Pacific Northwest region of North America (e.g., Pabst and Spies, 1999; Nierenberg and Hibbs, 2000; Hibbs and Bower, 2001; Anderson and Meleason, 2009), but also from other regions (e.g., Suzuki et al., 2002). There is much less research on structural and regeneration dynamics of harvested RMZs (e.g., Gregory, 1997; Gomi et al., 2006), although many jurisdictions allow such harvesting (Blinn and Kilgore, 2001). Understanding regeneration and structural dynamics in harvested RMZs is important because the sustainability of services provided by RMZs depends on maintenance of some forest cover over time, as well as the ability to regenerate desired tree species. For example, Minnesota's riparian management guidelines recommend maintaining some forest cover in the RMZ along cold-water streams, to better regulate stream temperature and organic matter flux, as well as increase the component of longer-lived, later successional hardwoods and conifers, as habitat elements for riparian dependent species and as a source of persistent dead wood (Minnesota Forest Resources Council, 2005). Where timber harvesting guidelines for RMZs fail to meet these broader ecological objectives, the sustainability of riparian resources might be compromised.

Here we address changes in overstory and regeneration layers of managed riparian areas in northern Minnesota, USA. The study stands were treated using RMZ width and residual tree guidelines developed for the state of Minnesota (Minnesota Department of Natural Resources, 1995). In an earlier study, we focused on vegetative regeneration of *Populus* (aspen) species in the third year after treatment (Palik et al., 2003); here we focus on 9th year stand structure and regeneration results in a more comprehensive manner. Specifically, we quantified changes in overstory structure over the nine year period and examined how treatments, that included partial harvesting and passive management, influenced regeneration of different species groups, including early successional species, late successional hardwoods, conifers, sub-canopy trees, and woody shrubs. Secondly, we examined regeneration dynamics in RMZs cut using different harvesting systems: namely cut-to-length harvesting, which de-limbs and cuts logs to length at the stump, and tree-length harvesting, which de-limbs at the stump, but then skids the full bole to a landing for processing (Mattson et al., 1999). These two systems are thought to differ in degree of site impact (Gingras, 1994; Lanford and Stokes, 1995) and, potentially, they could influence forest regeneration in different ways. We address our objectives using an operational-scale management experiment that included: replication of treatments, a full control (i.e., no cutting in upland or riparian area), a riparian control (i.e., upland harvested but RMZ uncut), pre-harvest sampling, and several years of post-harvest sampling.

2. Methods

2.1. Study site

The study area is located in the Laurentian Mixed Forest Province (Minnesota Department of Natural Resources, 2003) in southern Itasca County, Minnesota, USA (47°14′14″N, 93°31′49″W) on land owned and managed by UPM Blandin Paper Company (Fig. 1). Upland soils were generally well-drained, fertile loams. The climate is cold temperate with mean annual temperatures of 3.9 °C and mean annual precipitation of 70.0 cm. The study area consisted of a series of small watersheds drained by four first order streams (Fig. 1). Bank-full widths of the streams ranged from 1.5 to 4.7 m. Major valley floor landforms included narrow floodplains, ranging from 4 to 16 m wide, one or two fluvial terraces, and hill slopes leading into the glacially deposited upland. Valley widths ranged from 37 to 87 m.

Pre-harvest, upland forest ecosystems of the study area were dominated by *Acer saccharum* (sugar maple), *Betula papyrifera* (paper birch), *Tilia americana* (basswood), and *Populus tremuloides* (trembling aspen), with lesser amounts of *Populus grandidenta* (bigtooth aspen), *Abies balsamea* (balsam fir), *Picea glauca* (white spruce) and *Pinus strobus* (eastern white pine) (Table 1). *Fraxinus nigra* (black ash) and *Thuja occidentalis* (eastern white cedar) occurred on the small floodplains. Throughout both the uplands and the small floodplains, *Ostrya virginiana* (ironwood) was the primary understory tree species, while *Corylus cornuta* (beaked hazel), *Acer spicatum* (mountain maple), and *Salix* (willow) were the primary woody shrubs. The largely even-aged forest became established after logging early in the 20th century.

2.2. Experimental design

We established 12 treatment stands along the streams in 1996, each 4.8 ha in size (2.4 ha on each side of the stream) (Fig. 1). In each stand, the fixed-width RMZ consisted of a 60 m-wide strip centered on the stream (30 m on each side). The length of the stream reach contained in each RMZ ranged from 135 to 200 m, depending on meander length within the treatment stand.

Our experiment used a constrained randomized design, with four treatments replicated three times (Fig. 1). Treatments were assigned randomly among the 12 stands, except that full controls (see below) were constrained to be upstream of all treatments on a particular stream segment. The uplands in nine of the 12 stands were clearcut, using either a cut-to-length or a tree-length harvesting system. In the former, trees are mechanically felled, topped, de-limbed, and cut into shortwood lengths at the stump, and then removed off-site using a tracked or six-tired forwarder. In the latter system, trees were mechanically felled and then limbed and topped in the woods using a chainsaw with tree-length boles skidded to the landing. We cut the RMZs in six of the nine stands, using the same system as in the upland, to a residual basal area of about 13 m^2/ha. Trees to be removed within the RMZs and RMZ boundaries were marked with paint by study personnel. We left the RMZs intact on the remaining three upland clearcut stands (riparian control). An additional three stands were full controls, with no harvesting in the RMZs or adjacent uplands. All landings were located outside of the stands. Harvesting was completed in late summer-early fall of 1997 by one logging contractor.

2.3. Vegetation sampling

Prior to the harvest in each stand, we established transects running perpendicular to the stream. The number of transects ranged from 5 to 8 per stand depending on unit width and alternated between sides of the stream so that we might better capture the full range of environmental heterogeneity along a reach. We established permanent sample points along the transects, centered on major landforms (e.g., floodplain, terrace, hill slope). The number of points per stand ranged from 16 to 42, depending on number of transects and the number of landforms along each transect. At each point, we recorded data on overstory structure and composition as well as sapling and regeneration (advance regeneration prior to harvest; new and surviving regeneration after harvest) composition

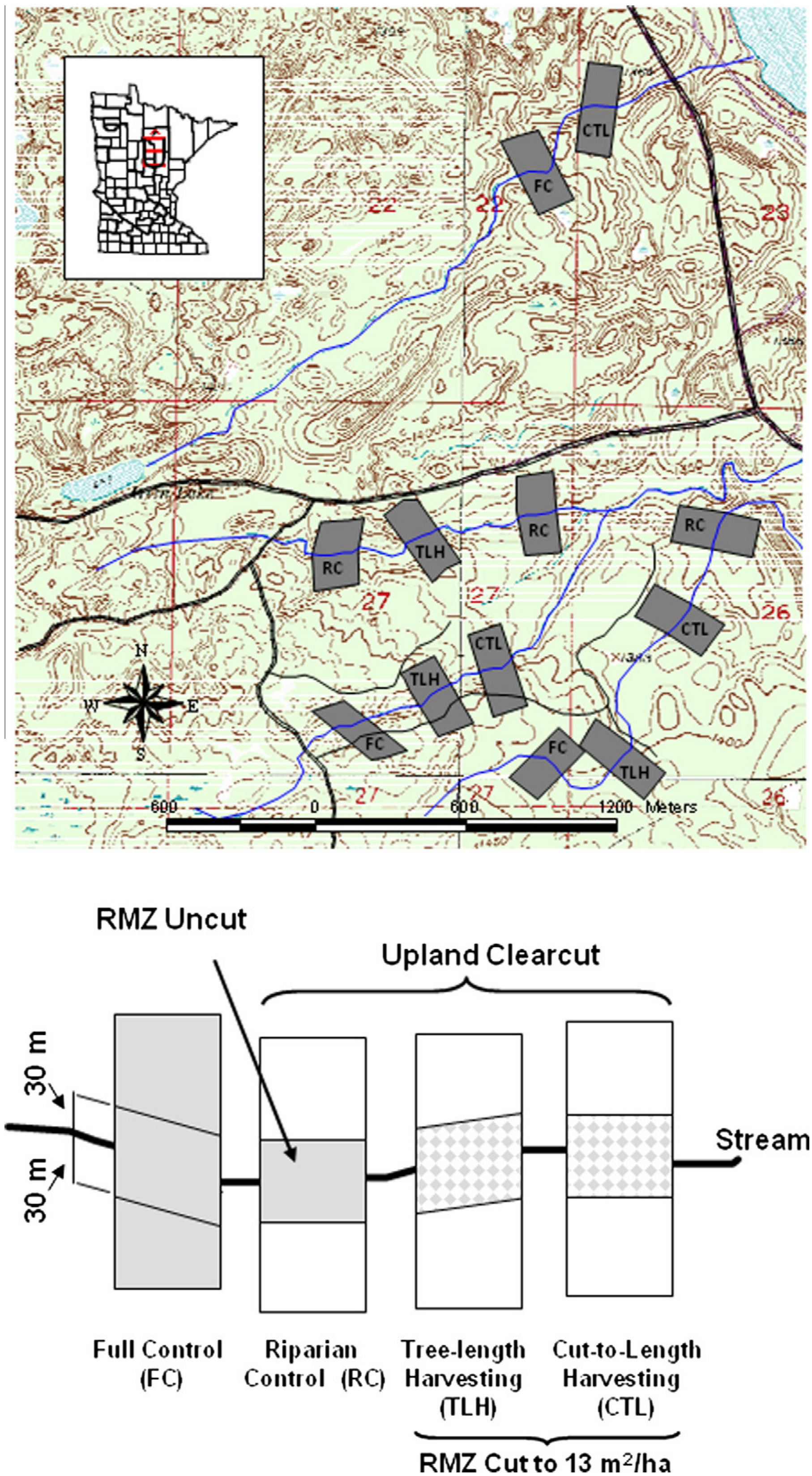

Fig. 1. Map of study location and diagrammatic representation of harvest treatments in riparian management zones (RMZ).

and abundance. We sampled overstory trees ($\geqslant$10 cm diameter at 1.4 m; dbh) using the point-quarter method (following Brower and Zar, 1984). At each point, we recorded the species, diameter (at 1.4 m), and distance to the closest tree in each of four quarters around the point on the landform where the point occurred. We sampled the sapling layer (2.5 $\leqslant$ dbh < 10 cm) using the same method and the same points as the overstory. We sampled regeneration (dbh < 2.5 cm) by species in nested plots centered on each

Table 1
Overstory basal area in four riparian harvest treatments at different sample periods.

	Basal area (m^2/ha)								
Harvest treatment[a]	Sample period	Total	*Populus*[b]	*Ace saccharum*	*Tilia americana*	*Betula papyrifera*	*Fraxinus nigra*	*Abies balsamea*	Other[c]
Full control	Pre-harvest	28.0 (1.4)[d]	5.7 (2.1)	6.3 (1.5)	4.2 (0.6)	4.3 (1.6)	4.5 (1.3)	0.6 (0.3)	2.3 (1.4)
	1 year-Post[e]	–	–	–	–	–	–	–	–
	9 year-Post	28.0 (1.4)	4.2 (1.6)	7.2 (1.0)	4.7 (0.9)	4.9 (2.4)	4.0 (1.9)	0.4 (0.4)	2.7 (0.9)
Riparian control	Pre-harvest	28.0 (1.3)	3.6 (1.9)	2.3 (0.7)	0.4 (0.3)	5.4 (1.6)	5.8 (2.0)	5.3 (1.7)	5.3 (1.6)
	1 year-Post[e]	–	–	–	–	–	–	–	–
	9 year-Post	20.4 (4.2)	2.7 (1.6)	2.8 (0.5)	0.2 (0.2)	4.4 (1.8)	4.5 (1.1)	2.4 (0.4)	3.4 (1.6)
Partial harvest-CTL	Pre-harvest	26.5 (2.8)	5.6 (2.2)	3.7 (1.7)	3.6 (1.7)	2.9 (0.7)	3.0 (1.5)	1.9 (0.3)	5.5 (1.9)
	1 yr-Post	13.0 (1.7)	2.3 (2.0)	1.2 (0.5)	2.2 (0.8)	0.6 (0.1)	1.9 (0.3)	0.5 (0.3)	4.4 (1.0)
	9 yr-Post	5.9 (1.2)	0.9 (0.5)	1.4 (0.6)	0.7 (0.5)	0.5 (0.2)	0.5 (0.1)	0.1 (0.1)	1.8 (0.7)
Partial harvest-WT	Pre-harvest	33.8 (2.0)	7.1 (1.7)	5.6 (3.0)	2.3 (1.2)	5.5 (1.6)	5.0 (2.0)	2.1 (0.9)	6.1 (1.4)
	1 yr-Post	13.1 (1.7)	1.4 (0.2)	1.9 (0.4)	1.5 (0.5)	1.5 (0.4)	3.3 (0.7)	1.0 (0.3)	2.6 (0.6)
	9 yr-Post	6.4 (0.8)	0.3 (0.1)	2.3 (0.6)	0.4 (0.2)	0.5 (0.2)	1.3 (0.2)	0.3 (0.1)	1.3 (0.4)

[a] Harvest treatment: Full control = no harvest in riparian management zone (RMZ) or in adjacent upland; Riparian control = no harvest in RMZ, adjacent upland clearcut; Partial harvest-CTL = RMZ partially harvested using cut-to-length processing, upland clearcut using the same system; Partial harvest-TL = RMZ partially harvested using tree-length harvesting, upland clearcut using the same system.
[b] Includes *Populus grandidentata*, *Populus tremuloides*, and *Populus balsamifera*.
[c] Other species include: *Ulmus americana*, *Thuja occidentalis*, *Ostrya virginiana*, *Quercus rubra*, *Pinus strobus*, *Picea glauca*, and *Betula alleghaniensis*.
[d] Values are means of four replicates (±1 standard deviation).
[e] 1 year-Post-harvest was assumed unchanged from pre-harvest for the full control and the riparian control.

point, including 0.5 m^2 square plots for stems <1 m tall and 7 m^2 circular plots for stems $\geqslant$1 m tall and <2.5 cm dbh). We collected pre-harvest vegetation data in the summer of 1997 (overstory, sapling, and regeneration layers in all treatments) and post-harvest data in 1998 (overstory in RMZ harvest treatments only, regeneration in all treatments), 2000 (regeneration layer in all treatments) and 2006 (overstory, sapling, and regeneration layers in all treatments). Response variables were summarized at the RMZ-scale, as means for each treatment and year.

2.4. Analyses

We used nonmetric multidimensional scaling (NMS) run in PC-ORD (McCune and Mefford, 2006) to graphically display and interpret woody community compositional differences within the regeneration layer (stems < 2.5 cm dbh) and sapling layer (2.5 $\leqslant$ dbh < 10 cm) among treatments over time. The data matrices consisted of RMZ treatment stands (rows) and densities of woody species that occurred in at least three RMZs (columns). Values were square-root transformed prior to analysis to reduce the influence of highly abundant species. NMS relaxes assumptions of normality and linear relationships to environmental variables, provides a biologically meaningful view of data, and preserves distance properties among sample units (RMZ stands, in our case) (Clark, 1993; McCune and Grace, 2002). We used Sorenson (Bray-Curtis) distance measures (the default PC-ORD), and specified 6 dimensions and 250 iterations (with actual data) for the initial analysis. Significance of dimensional solutions was assessed using Monte Carlo permutation procedures. Our final ordination was restricted to 3 dimensions for the regeneration layer and 2 dimensions for the sapling layer, based on stress reduction and examination of scree plots (McCune and Grace, 2002). To better display temporal trends among treatments graphically, we averaged the three site (RMZ) scores for each treatment and each year of analysis to derive a mean score for a treatment at a given time.

Following NMS, we used a multi-response permutation procedure (MRPP, Biondini et al., 1988), run using PC-ORD, to identify differences among treatments groups. MRPP is a nonparametric multivariate procedure useful for comparisons among previously defined groups of sampling units (McCune and Grace, 2002). We ran MRPP using a Euclidean distance measure (the default in PC-ORD). If the overall test was significant (at $p \leqslant 0.10$), we performed pair-wise comparisons to clarify differences among treatment groups.

Mean densities of various combined groups of species (total density, early successional, later successional deciduous, conifers, sub-canopy species) were compared within years and among treatments using completely randomized one-way ANOVA. We combined individual species within these categories to reduce the influence of highly variable densities of individual species, but also to address our question about the influence of RMZ treatment on regeneration of various species groups (i.e., later successional species and conifers). If the overall test was significant (at $p \leqslant 0.10$), then harvest treatments were compared using Tukey's test. Before analysis, we assessed variance and normality of the data and in some cases transformed the original data (square-root or log) to better meet the assumptions of ANOVA.

3. Results

3.1. Changes in overstory structure with treatment and over time

Pre-harvest overstory basal areas were similar for the four RMZ treatments, averaging about 29 m^2/ha (Table 1). *Acer saccharum*, *Betula papyrifera*, *Tilia americana*, *Populus*, *Fraxinus nigra*, and *Abies balsamea* dominated the pre-harvest forest, comprising 85% of relative basal area (Table 1). One-year post-harvest basal areas in the two RMZ harvest treatments (cut-to-length, tree-length) averaged about 13.0 m^2/ha (Table 1). Post-harvest overstory composition was similar to pre-harvest composition (in a relative sense). Nine years after treatment, total basal areas of the two partial-harvest treatments had decreased by more than 50% below the initial post-harvest treatments, to around 6 m^2/ha (Table 1). Basal area in the riparian control treatment decreased from 28 to 20 m^2/ha over the nine years. In all cases, the reductions were due to blowdown of residual trees in the RMZs (personal observation).

3.2. Regeneration composition

Compositional differences among treatments in the regeneration layer (dbh < 2.5 cm) were evident in NMS ordination. The final three-dimensional configuration had greater structure than expected by chance ($p = 0.02$), with stress of 13.05 and final instability of 0.00001. Eighty-four percent of total variation was accounted for on the three axes, and 73% on axes 2 and 3, the two dominant axes (Fig. 2).

On average, the RMZs were similar in regeneration composition prior to treatment (symbols relatively close together within the oval in Fig. 2). The MRPP confirmed this, as there was no more heterogeneity in species composition among treatments than expected by chance ($T = -0.17$, $A = 0.0099$, $p = 0.40$).

After treatment and over time, the full control RMZs did not change much in regeneration layer composition. In contrast, the three harvest treatments displayed increasingly greater deviation from their starting conditions and from the full control (Fig. 2). In particular, the two partial-harvest treatments (cut-to-length, tree-length) displayed relatively large and similar deviation from the full control and riparian control treatments over time, while the latter treatment was intermediate between the full control and partial harvest treatments. The MRPP of nine-year post-harvest composition confirmed this response, as there was less heterogeneity of species communities within treatments, and more heterogeneity among treatments, than expected by chance ($T = -3.50$, $A = 0.243$, $p = 0.003$). Pair-wise comparisons verified treatment differences. The regeneration community of the full control treatment was significantly different than that of the three harvest treatments ($p = 0.02$–0.03), the riparian control was significantly different than the two partial-harvest treatments ($p = 0.06$); while the latter two treatments were not significantly different ($p = 0.90$).

Several species had high positive correlations ($r \geqslant 0.6$) with NMS axis 2, including *Betula papyrifera* ($r = 0.82$), *Populus* sp. ($r = 0.78$), *Acer rubrum* (red maple; $r = 0.67$), *Acer spicatum* ($r = 0.63$), *Corylus cornuta* ($r = 0.63$), and *Salix* sp. ($r = 0.60$). These taxa all increased in abundance over time, particularly in the two partial-harvest treatments.

3.3. Regeneration densities

There were no significant differences among treatments in total density or densities of composite species groups in the pre-harvest year ($p = 0.23$–0.87) (Fig. 3a–f). However, by nine years after harvest, total regeneration density varied among treatments ($p = 0.008$) (Fig. 3a). Specifically, total densities of the two-partial harvest treatments were significantly higher than the full control ($p = 0.02$ and $p = 0.03$, respectively) and riparian control ($p = 0.04$ and $p = 0.07$, respectively), but did not differ from each other ($p = 0.97$). Densities of the riparian control and full control also did not differ from each other ($p = 0.93$).

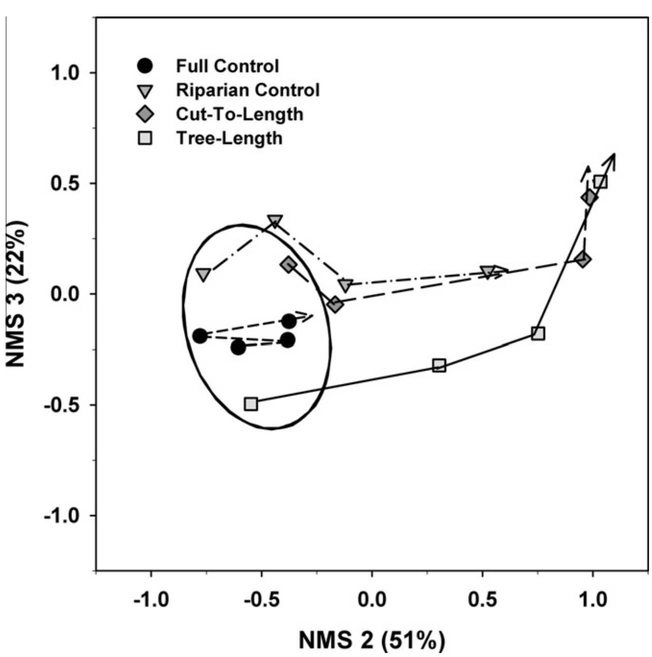

Fig. 2. Non-metric, multidimensional scaling ordination of regeneration layer treatment scores over time. For each treatment, the temporal progression runs from pre-treatment, to one year after treatment, to three years after treatment, to nine years after treatment. The starting positions in the pre-harvest year for each treatment are enclosed by the oval in the biplot.

Densities of early successional trees were marginally different among treatments nine years after treatment ($p = 0.09$) (Fig. 3b). Specifically, density of the cut-to-length treatment was significantly higher than the full control ($p = 0.07$). None of the other comparisons were significant ($p = 0.34$–0.82), although mean densities of the tree-length and riparian control treatments were higher than the full control. Densities of later successional trees nine year after treatment were marginally different among treatments ($p = 0.08$), but none of the individual comparisons were significant ($p = 0.13$–0.99), although the trend among treatment means was similar to that for total density (Fig. 3c). Conifer densities did not differ among treatments nine years after harvest ($p = 0.41$) (Fig. 3d). Densities of subcanopy tree species differed among treatments ($p = 0.04$), but only the comparison of the full control to the cut-to-length treatment was significant, with the latter having higher density than the former ($p = 0.06$) (Fig. 3e). Finally, woody shrub densities differed significantly among treatments ($p = 0.03$) (Fig. 3f). Densities of the cut-to-length and tree-length treatments were significantly higher than the full control ($p = 0.05$ and $p = 0.06$, respectively), but not the riparian control ($p = 0.17$ and $p = 0.18$, respectively). Densities of the cut-to-length and tree-length treatments did not differ ($p = 0.99$), nor did densities of the riparian control and full control ($p = 0.87$).

3.4. Sapling composition

Compositional differences among treatments in the sapling layer ($2.5 \leqslant$ dbh < 10.0 cm) were evident in the NMS ordination (Fig. 4). A final two-dimensional configuration had greater structure than expected by chance ($p = 0.004$), with stress of 11.23 and final instability <0.00001. Ninety-three percent of total variation was accounted for on the first two axes.

On average, the RMZs were similar in sapling composition prior to treatment (symbols relatively close together within the oval in Fig. 4). The MRPP confirmed this, as heterogeneity in species composition among treatments was not greater than expected by chance ($T = -1.04$, $A = 0.073$, $p = 0.15$).

By nine years after harvest, the full control RMZs had not changed much in composition (Fig. 4). In contrast, the three harvest treatments deviated from their starting conditions and from the full control. In particular, the two partial-harvest treatments (cut-to-length, tree-length) displayed relatively large and similar deviation from the full control and riparian control treatments over time, while the latter treatment was intermediate between the full control and partial-harvest treatments. The MRPP on nine-year post-harvest composition data confirmed this response, as there was less heterogeneity of species communities within treatments, and more heterogeneity among treatments, than expected by chance ($T = -3.43$, $A = 0.273$, $p = 0.004$). Pairwise comparisons verified treatment differences. The sapling community of the full control treatment was significantly different than the three harvest treatments ($p = 0.02$–0.03) and the riparian control was significantly different than the two partial-harvest treatments ($p = 0.03$); while the latter two treatments were not significantly different from each other ($p = 0.94$).

Several species had high negative correlations ($r \geqslant -0.6$) with NMS axis1, including *Betula papyrifera* ($r = -0.79$), *Populus* sp. ($r = -0.77$), and *Acer spicatum* ($r = -0.78$). These taxa all increased in abundance over time, particularly in the two partial harvest treatments. *Acer saccharum* ($r = 0.65$) had a high positive correlation with axis 1 and was largely associated with starting conditions

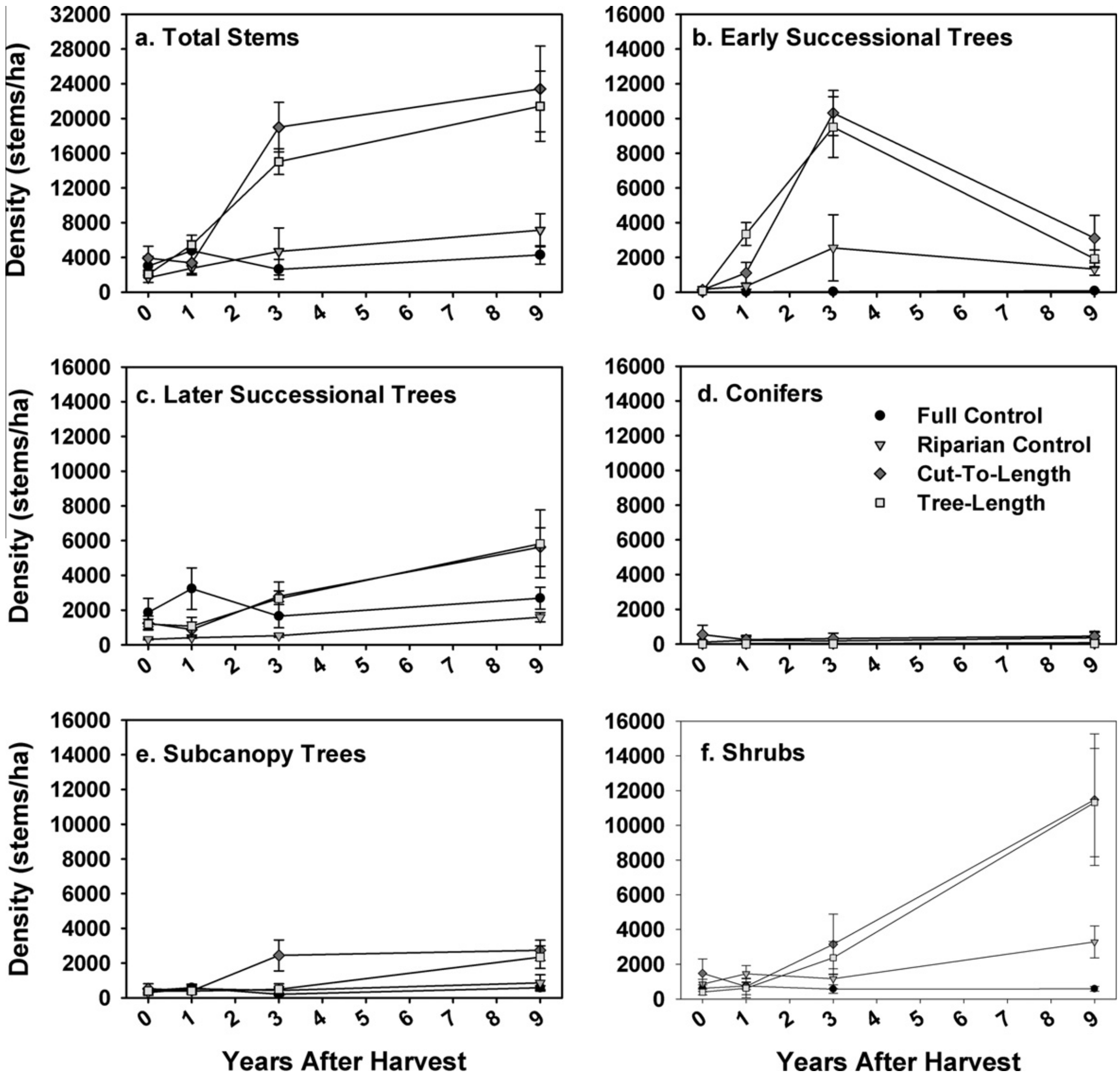

Fig. 3. Regeneration layer densities over time in four riparian management zone treatments: (a) total stem densities, (b) early successional tree densities, (c) late successional tree densities, (d) conifer densities, (e) sub-canopy tree species densities, (f) woody shrub densities. Values are means of three replicates ± standard error. Note: *y*-axis scale differs between a and b–f. Year zero is the pre-harvest value.

prior to harvest in all treatments and the full control treatment nine years after harvest. *Populus* sp. ($r = 0.84$) and *Tilia americana* ($p = 0.66$) had positive correlations with axis 2, indicating increases in abundance in the treatment RMZs by nine years after harvest.

3.5. Sapling densities

There were no significant differences among treatments in total sapling density or densities of composite groups in the pre-harvest year ($p = 0.23–0.87$) (Fig. 5a–e). However, by nine years after harvest, total sapling density was significantly different among treatments ($p = 0.008$) (Fig. 5a). Specifically, total densities of the two partial-harvest treatments were both significantly higher than the full control ($p = 0.02$ and $p = 0.03$, respectively) and riparian control ($p = 0.04$ and $p = 0.07$, respectively), but did not differ from each other ($p = 0.97$). Densities of the riparian control and full control also did not differ from each other ($p = 0.93$).

Densities of early successional trees were significantly different among treatments ($p = 0.004$) (Fig. 5b). Specifically, densities in the cut-to-length and tree-length treatments were significantly higher than the full control ($p = 0.015$ and $p = 0.017$, respectively) and riparian control ($p = 0.025$ and $p = 0.030$, respectively), but did not differ from each other ($p = 0.999$). Densities of the full control and riparian control also did not differ from each other ($p = 0.971$). Densities of later successional trees, conifers, and subcanopy tree species did not differ among treatments ($p = 0.22–0.54$) (Fig. 5c–e). There were no sapling sized individuals of shrub species.

4. Discussion

4.1. RMZ dynamics

Our results, nine years after treatment, indicate that an initial removal of about 57% of the basal area within RMZs that were adjacent to clearcuts initiated a strong regeneration response, including an increase in total density of stems and a change in species composition, compared to the uncut RMZ. The overstory removal/response relationship likely also was influenced by the additional reduction of basal area, from 13 to 6 m^2/ha, that occurred over time due to blowdown of residual trees.

For the most part, regeneration composition and abundance within the riparian control treatment (RMZ uncut, adjacent upland clearcut) were similar to the full control. This suggests that (1) the

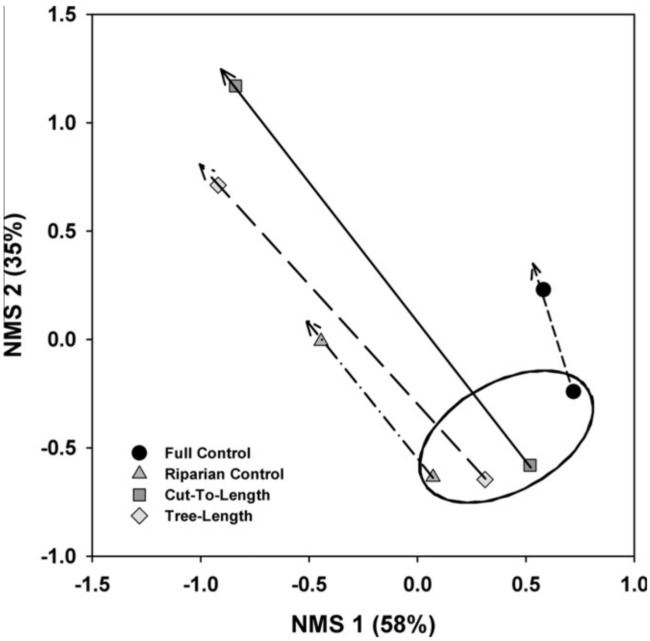

Fig. 4. Non-metric, multidimensional scaling ordination of sapling layer treatment scores over time. For each treatment, the temporal progression runs from pre-treatment, to nine years after treatment; there were no measurements of saplings in the first or third years after treatment. The starting positions in the pre-treatment year for each treatment are enclosed by the oval in the biplot.

reduction of residual basal area from blowdown in this treatment, from 28 to 20 m^2/ha, was not enough to elicit a strong regeneration response within the RMZ and (2) the changes that occurred in the partially-harvested RMZs were likely due primarily to increases in resources from overstory removal directly within the RMZ, as opposed to edge effects associated with the adjacent clearcut. Studies on edge effects document increases in stem densities and understory cover in forest edge, extending anywhere from 15 to 40 m into the stand (Palik and Murphy, 1990; Murcia, 1995; Harper et al., 2005, 2007). Increased solar radiation and higher soil and air temperatures occur in forest edges, relative to the interior, and these increases can extend 20–60 m into the forest, depending on edge orientation (Young and Mitchell, 1994; Chen et al., 1995). While similar microclimatic changes likely occurred in our RMZs since they were only 30 m wide, the effect was apparently overshadowed by the increase in resources associated with harvesting within the RMZ proper.

4.2. Regeneration composition

The compositional responses of regeneration in the partially-harvested RMZs was driven by an increase in early successional tree species, largely *Populus tremuloides*, but also some *Populus grandidentata* and *Betula papyrifera*. Woody shrub density, principally *Corylus cornuta* and *Salix* sp., also increased substantially in the partial harvest treatments, contributing about 50% of total stem density by the 9th year after harvest.

By the 9th year after harvest, the density of early successional species in the regeneration layer was only marginally higher in the partial-harvest treatments, compared to the full control (although it had been much higher in these treatments in the 3rd year after harvest), but this is because individuals of these fast growing species had moved into the sapling size class by this time, where their density was significantly higher than the full and riparian controls. Over 80% of the stems in this group were *Populus* (most likely root suckers). Depending on the source examined, *Populus* sucker densities in the two RMZ partial-harvest treatments (averaging about 2300/ha in the two treatments) were either within the range of full stocking for a commercial stand (e.g., 2285 stems/ha at age 9; Stoeckeler and Macon, 1956) or well below full stocking (e.g., 4000–9000 stems/ha at age 8–10; Perala, 1983; Doucet and Boivin, 1985). Reduced sucker density compared to what would be found in a clearcut is not surprising, as others report reductions in sucker densities at even lower levels of overstory

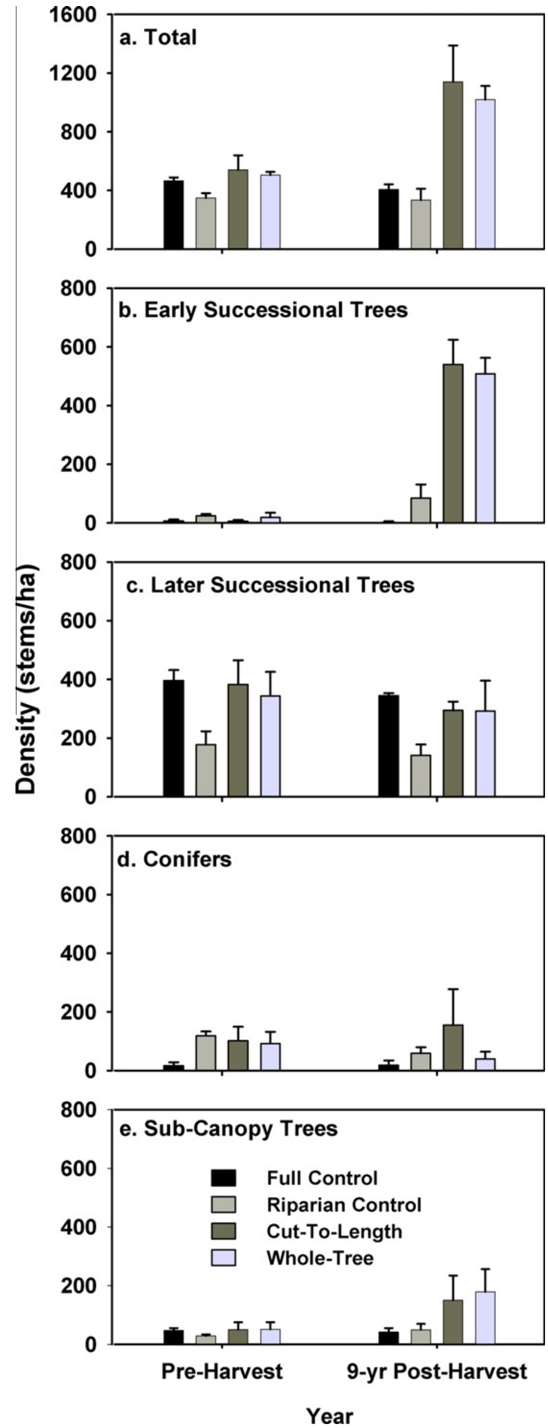

Fig. 5. Sapling layer densities pre-treatment and nine years after treatment in four riparian management zone treatments: (a) total stem densities, (b) early successional tree densities, (c) late successional tree densities, (d) conifer densities, (e) sub-canopy tree species densities. Values are means of three replicates ± standard error. Note: *y*-axis scale differs between a and b–e.

retention than our RMZs started with after harvest (Huffman et al., 1999; Stone et al., 2001).

We found no increase in conifer regeneration, despite the local occurrence of seed sources for several conifer species, including *Abies balsamea*, *Picea glauca*, *Pinus strobus*, and *Thuja occidentalis.* Densities of these species may not been high enough to provide adequate seed to the study stands. The density of later successional tree species in the regeneration layer was marginally higher in the partial-harvest treatments compared to the full control (although no individual pair-wise contrast was significant). Subcanopy tree species density in the regeneration layer (but not the sapling layer) was significantly higher (although low as a percentage of total stems) in the cut-to-length treatment compared to the full control. This response was driven mostly by an increase in shade tolerant species, including *Ostrya virginiana* and *Acer spicatum*.

Taken as a whole, our results indicate that the RMZ treatments used in our study and that are also the basis for riparian management guidelines in Minnesota and elsewhere in the Great Lakes regions, largely result in regeneration of a forest dominated by early successional species. Moreover, the treatments themselves, while initially maintaining over 40% of original basal area in the overstory, failed to maintain this canopy cover over time due to blowdown of residual trees. The reduction in residual overstory overtime likely contributed to the regeneration response of early successional and woody shrub species that we document. That is, the increases in regeneration density and composition changes may have been less substantial had basal area remained near the initial post-harvest values.

4.3. Responses to harvest systems

Regeneration responses were similar with cut-to-length and tree-length harvesting systems; both treatments were associated with significant increases of early successional species (*Populus* and *Betula papyrifera*) and woody shrubs, compared to the full control. The two systems did not differ significantly in response of any regeneration variable. This suggests that the choice of one system over the other for harvesting an RMZ may have little effect on near-term compositional development.

Others report that cut-to-length harvesting systems result in less site disturbance (e.g., less ground disturbance and mineral soil exposure, less area that is heavily trafficked, less compaction) and better protection of advance regeneration and residual trees than harvesting systems using skidders (Gingras, 1994, 1995; Richardson and Makkonen, 1994; Lanford and Stokes, 1995; Limbeck-Lilienau, 2003). In our study, the tree-length system did expose more organic and mineral soil, displace more soil, and traffic more area than the cut-to-length system (Perry et al., 1998, 2001). However, the similarity of ninth year post-harvest regeneration responses suggests that differences between harvest systems in site impacts did not result in regeneration differences.

4.4. Management implications

Passive management of RMZs, that is leaving them alone, is a common silvicultural approach in many regions (e.g., Hirofumi et al., 2005; Hibbs and Bower, 2001). For a forest manager, this approach takes less time during design and administration and it lessens concerns over impacts to water quality and riparian and aquatic habitat from harvesting. A legitimate concern with this approach is that forest dynamics after RMZ establishment may not lead to desired future conditions for the riparian area (Berg, 1995), either in terms of desired commercial timber species or conditions that sustain ecological services.

For example, in the Great Lakes region, one desired condition is to manage for commercial stands of *Populus* in the RMZ concurrently with the adjacent, often clearcut, upland forest. An alternate desired condition, as stated in best management guidelines for the region, is to maintain at least partial continuous canopy cover over time and to increase the abundance of long-lived, late successional tree species, particularly conifers, to promote among other values, an increase in the input of large-sized, persistent wood into the stream (e.g., Minnesota Forest Resources Council, 2005; Wisconsin Department of Natural Resources, 2011).

Our results indicate that it may be difficult to maintain moderate canopy cover or to increase latter successional or conifer tree species, in settings like those we studied, using a similar partial harvesting approach. *Populus* will likely be a large component of similarly treated RMZs in similar settings. Regeneration of long-lived conifer species may be limited with partial harvest, and with passive management, if seed sources are limited. Moreover, high abundance of woody shrubs in treated RMZs may inhibit establishment of desired tree species and compete with those that do establish (Dovciak et al., 2003; Weyenberg et al., 2004). The instability of the 30 m-wide RMZs due to blowdown in both treated and passive RMZs, a finding common in other studies (Grizzel and Wolff, 1998; McClure et al., 2004), also compromises the long-term sustainability of riparian ecological functions dependent on canopy cover and large trees. Achieving desired conditions of at least moderate continuous canopy cover and more long-lived, later successional, and conifer species will require a comprehensive silvicultural approach for an RMZ, focused on ensuring adequate regeneration of desired tree species, perhaps through underplanting (Carroll, 1994; MacKinnon, 1994; Hayes et al., 1996; Palik et al., 1999), competition control to increase survival and growth of these species, and higher initial residual basal area to "buffer" against expected blowdown overtime.

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References

Anderson, P.D., Meleason, M.A., 2009. Discerning responses of downed wood and understory vegetation abundance to riparian buffer width and thinning treatments: an equivalence–inequivalence approach. Can. J. For. Res. 39, 2470–2485.

Belt, G.H., O'Laughlin, J., 1994. Buffer strip design for protecting water quality and fish habitat. West. J. Appl. For. 9, 42–44.

Berg, D.R., 1995. Riparian silvicultural system design and assessment in the Pacific Northwest Cascade Mountains. USA Ecol. Appl. 5, 87–96.

Biondini, M.E., Mielke Jr., P.W., Berry, K.J., 1988. Data-dependent permutation techniques for the analysis of ecological data. Vegetation 75, 161–168.

Blinn, C.R., Kilgore, M.A., 2001. Riparian management practices: a summary of state guidelines. J. For. 99, 11–17.

Broadmeadow, S., Nisbet, T.R., 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. Hydrol. Earth Syst. Sci. 8, 286–305.

Brosofske, K.D., Chen, J., Naiman, R.J., Franklin, J.F., 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecol. Appl. 7, 1188–1200.

Brower, J.E., Zar, J.H., 1984. Field and Laboratory Methods for General Ecology. Brown Publishers, Dubuque, Iowa, USA, W.C.

Burns, G.A., Whiting Jr., R.M., LeGrande, G.M., Dickson, J.G., 1999. Wildlife linkages: volumes and values of residual timber in riparian zones in eastern Texas. For. Ecol. Manage. 114, 321–327.

Carroll, H., 1994. Softwood management techniques in the riparian zone, in Proceedings of the Symposium on Riparian Zone Management. Canadian Forest Service-Maritimes Region, Natural Resources Canada, Fredericton, New Brunswick, Canada, pp. 91–94.

Chen, J., Franklin, J.F., Spies, T.A., 1995. Growing-season microclimatic gradients from clearcut edges into old-growth Douglas-fir forests. Ecol. Appl. 5, 74–86.

Clark, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol. 18, 117–143.

Darveau, M., Beauchesne, P., Bélanger, L., Huot, J., Larue, P., 1995. Riparian forest strips as habitat for breeding birds in boreal forest. J. Wild. Manage. 59, 67–78.

Darveau, M., Huot, J., Bélanger, L., 1998. Riparian forest strips as habitat for snowshoe hare in a boreal balsam fir forest. Can. J. For. Res. 28, 1494–1500.

Decker, R.C., 2003. Current regulations, guidelines, and Best Management Practices concerning forest harvesting and riparian zone management. Buffer Zone Working Group Report, Fisheries and Oceans Canada, St Johns, Newfoundland, Canada, p. 42.

Doucet, R., Boivin, J.-L., 1985. Evolution de la regeneration d'une tremblale au cours des dl! annees sulvant une coupe totale. Gouv. du Quebec, Min, de I'Energle et des Ress. Serv, de la rech for, Rapp Interne no 245, p. 31.

Dovciak, M., Frelich, L.E., Reich, P.B., 2003. Seed rain, safe sites, competing vegetation and soil resources spatially structure white pine regeneration and recruitment. Canadian J. For. Res. 33, 1892–1904.

Gingras, J.F., 1994. A comparison of full-tree versus cut-to-length systems in the Manitoba Model Forest. Forest Engineering Research Institute of Canada, Special, Report No. SR-92.

Gingras, J.F., 1995. Partial cutting in boreal mixedwoods: a comparison of productivity and site impacts with different harvesting systems. Forest Engineering Research Institute of Canada (FERIC), Field Note No. 4.

Gregory, S.V., 1997. Riparian Management in the 21st Century. In: Kohm, K.A., Franklin, J.F. (Eds.), Creating Forestry for the 21st Century. Island Press, Washington, D.C., USA, pp. 69–85.

Gomi, T., Sidle, R.C., Noguchi, S., Negishi, J.N., Abdul Rahim, N., Sasaki, S., 2006. Sediment and wood accumulations in humid tropical headwater streams: effects of logging and riparian buffers. For. Ecol. Manage. 224, 166–175.

Gregory, S.V., Swanson, F.J., McKee, W.A., Cummins, K.W., 1991. An ecosystem perspective on riparian zones. BioSci. 41, 540–551.

Grizzel, J.D., Wolff, N., 1998. Occurrence of windthrow in forest buffer strips and its effect on small streams in northwest Washington. Northw. Sci. 72, 214–223.

Harper, K.A., Macdonald, S.E., Burton, P.J., Chen, J., Brosofske, K.D., Saunders, S.C., Euskirchen, E.S., Roberts, D., Jaiteh, M.S., Essen, P.-E., 2005. Edge influence on forest structure and composition in fragmented landscapes. Conserv. Biol. 19, 768–782.

Harper, K.A., Mascarua-Lopez, L., Macdonald, S.E., Drapeau, P., 2007. Interaction of edge influence from multiple edges: examples from narrow corridors. Plant Ecol. 192, 71–84.

Hayes, J.P., Adam, M.D., Bateman, D., Dent, E., Emmingham, W.H., Maas, K.G., Skaugset, A.E., 1996. Integrating research and forest management in riparian areas of the Oregon Coast Range. West. J. Appl. For. 11, 85–89.

Hibbs, D.E., Bower, A.L., 2001. Riparian forests in the Oregon Coast Range. For. Ecol. Manage. 154, 201–213.

Hirofumi, K., Tomohiro, N., Yasuhiko, O., Yoshio, A., Hiromichi, F., Tomomasa, A., Kunihiro, T., Yasuhiro, Y., 2005. Status of riparian management zone and impacts of its preservation on forestry: case study of Mt. Iwate and the surrounding area, Iwate Prefecture. J. Japanese For. Soc. 87, 410–418.

Huffman, R.D., Fajvan, M.A., Bohall Wood, P., 1999. Effects of residual overstory on aspen development in Minnesota. Can. J. For. Res. 29, 284–289.

Lanford, B.L., Stokes, B.J., 1995. Comparison of two thinning systems. Part 1. Stand and site impacts. For. Prod. J 45, 74–79.

Laursen, S.B., 1996. A Description of the Riparian Forest Resource in the State of Minnesota. In: Laursen, S.B. (Ed.), At the Water's edge: The Science of Riparian Forestry. Minnesota Extension Service University of Minnesota, St. Paul, Minnesota, USA, pp. 15–20.

Limbeck-Lilienau, B., 2003. Residual stand damage caused by mechanized harvesting systems. Proceedings, AUSTRO 2003 in Schlägl/Austria, p. 11p.

Lowrance, R., Todd, R., Fail Jr., J., Hendrickson Jr., O., Leonard, R., Asmussen, L., 1984. Riparian forest as nutrient filters in agricultural watersheds. BioSci. 34, 374–377.

Lugo, A., 1995. Management of tropical biodiversity. Ecol. Appl. 5, 956–961.

MacKinnon, W., 1994. Silvicultural recommendations for riparian zones on Prince Edward Island, in: Proceedings of the Symposium on Riparian Zone Management. Canadian Forest Service-Maritimes Region, Natural Resources Canada, New Brunswick, Canada, pp. 95–98.

Mattson, J., Baumgras, J.E., Blinn, C.R., Thompson, M.A., 1999. Harvesting Options for Riparian Areas. In: Verry, E.S., Hornbeck, J.W., Dolloff, C.A. (Eds.), Managing Riparian Areas of the Eastern United States. Lewis Publishers, Baca Raton, Florida, USA, pp. 255–272.

McClure, J.D., Kolka, R.K., White, A., 2004. Effect of forest harvesting best management practices on coarse woody debris distribution in stream and riparian zones in three Appalachian watersheds. Water, Air, Soil Pollution: Focus 4, 245–261.

McCune, B., Grace, J.B., 2002. Analysis of ecological communities. MjM Software, Gleneden Beach, Oregon, USA.

McCune, B., Mefford, M.J., 2006. PC-ORD. Multivariate analysis of ecological data. Version 5. MjM Software, Gleneden Beach, Oregon, USA.

Minnesota Department of Natural Resources, 1995. Protecting water quality and wetlands in forest management: best management practices in Minnesota. Division of Forestry, Department of Natural Resources, St. Paul, MN, USA. p. 132.

Minnesota Department of Natural Resources, 2003. Field guide to the native plant communities of Minnesota: the Laurentian Mixed Forest Province. Ecological Land Classification Program, Minnesota County Biological Survey, and Natural Heritage and Nongame Research Program, Department of Natural Resources, St. Paul, MN, USA. p. 352.

Minnesota Forest Resources Council, 2005. Sustaining Minnesota forest resources: Voluntary site-level fore management guidelines for landowners, loggers, and resource managers. Minnesota Forest Resources Council, St. Paul, Minnesota, USA.

Murcia, C., 1995. Edge effects in fragmented forests: Implications for conservation. TREE 10, 58–62.

Murphy, M.L., Heifetz, J., Johnson, S.W., Koski, K.V., Thedinga, J.F., 1986. Effects of clear-cut logging with and without buffer strips on juvenile salmonids in Alaskan streams. Can. J. Fish. Aquat. Sci. 43, 1521–1533.

Newbold, J.D., Erman, D.C., Roby, K.B., 1980. Effects of logging on macroinvertebrates in streams with and without buffer strips. Can. J. Fish. Aquat. Sci. 37, 1076–1085.

Nierenberg, T.R., Hibbs, D.E., 2000. A characterization of unmanaged riparian areas in the central Coast Range of western Oregon. For. Ecol. Manag. 129, 195–206.

Pabst, R.J., Spies, T.A., 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, USA. Canadian J. For. Res. 29, 1557–1573.

Palik, B.J., Murphy, P.G., 1990. Edge versus disturbance effects in beech-sugar maple forest fragments. For. Ecol. Manage. 32, 187–202.

Palik, B.J., Zasada, J., Hedman, C., 1999. Ecological considerations for riparian silviculture. In: Verry, E.S., Hornbeck, J.W., Dolloff, C.A. (Eds.), Managing riparian areas of the eastern United States. Lewis Publishers, Baca Raton, Florida, USA, pp. 233–254.

Palik, B., Cease, K., Egeland, L., Blinn, C., 2003. Regeneration in riparian management zones of northern hardwood-aspen forests: effects of residual overstory and harvest method. Northern J. Appl. Forest. 20, 79–84.

Perala, D.A., 1983. Shearing restores full productivity to sparse aspen stands. USDA For. Serv., North Central For. Exp. Sta., Res. Note NC-296, p. 4.

Perry, J., Blinn, C., Fox, M.K., Palik, B., Mattson, J., Thompson, M., Verry, S., Johnson, L., Richards, C., Newman, R., Merten, E., Dahlman, R., Emerson, P., 1998. Evaluating riparian area dynamics, management alternatives and impacts of harvest practices. Final Report. Minnesota Forest Resources Council, St. Paul Minnesota, USA, p. 50.

Perry, J., Blinn, C., Newman, R., Hemstad, N., Merten, E., Fredrick, K., Fox, M.K., Palik, B., Mattson, J., Thompson, M., Verry, S., Johnson, L., Richards, C., Stroom, K., Shoenberg, J., Dahlman, R., Emerson, P., 2001. Evaluating riparian area dynamics, management alternatives and impacts of harvest practices. Final Report. Minnesota Forest Resources Council, St. Paul Minnesota, USA, p. 60.

Peterjohn, W.T., Correll, D.L., 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology 65, 1466–1475.

Quinn, J.M., Boothroy, I.K.G., Smith, B.J., 2004. Riparian buffers mitigate effects of pine plantation logging on New Zealand streams. 2 Invertebrate communities. For. Ecol. Manag. 191, 129–146.

Richardson, R., Makkonen, I., 1994. The performance of cut-to-length systems in eastern Canada. Forest Engineering Research Institute of Canada (FERIC), Report No. TR-109.

Stoeckeler, J.H., Macon, J.W., 1956. Regeneration of aspen cutover areas in northern Wisconsin. J. For. 54, 13–16.

Stone, D.M., Elioff, J.D., Potter, D.V., Peterson, D.B., Wagner, R., 2001. Restoration of aspen-dominated ecosystems in the Lake States, in: Shepperd, W.D., Binkley, D., Bartos, D.L., Stohlgren, T.J., Eskew, L.G. (Eds.), Sustaining aspen in western landscapes: symposium proceedings, pp. 137–143. USDA For. Serv., Rocky Mountain Res. Stn., Proc. RMRS-P-18. p. 460.

Suzuki, W., Osumi, K., Masaki, T., Takahashi, K., Daimaru, H., Hoshizaki, K., 2002. Disturbance regimes and community structures of a riparian and an adjacent terrace stand in the Kanumazawa Riparian Research Forest, northern Japan. For. Ecol. Manag. 157, 285–301.

Weyenberg, S., Frelich, L.E., Reich, P.B., 2004. Logging versus fire: How does disturbance type influence the abundance of *Pinus strobus* regeneration. Silva Fennica 38, 179–194.

Wisconsin Department of Natural Resources, 2011. Chapter 5: Riparian areas and wetlands. Pub-FR-226 2011, Madison, Wisconsin, USA.

Young, A., Mitchell, N., 1994. Microclimate and vegetation edge effects in a fragmented podocarp-broadleaf forest in New Zealand. Biol. Conserv. 67, 63–72.