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Early Regeneration and Structural Responses to Patch Selection and Structural Retention in Second-Growth Northern Hardwoods

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Restoration of late-successional conditions to second-growth forests has become a management objective on many ownerships. For northern hardwood forests, restoration targets include a higher abundance of large trees and coarse woody debris and greater diversity of tree species and size classes. Patch-selection harvests 0.12 ha in size were applied in conjunction with structural restoration/enhancement treatments, including within-patch legacy tree retention and downed woody debris (DWD) creation, to determine the effectiveness of these approaches at recruiting late-successional structure and intolerant and midtolerant tree species. Annual mortality rate of retained legacy trees was quite low over the 3 years postharvest (1.7%) and individual legacy tree diameter growth rate ranged from 0.2–1.0 cm yr^{-1}. Felling and retention of culls generated within-gap DWD volumes similar to old-growth levels. Sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), and striped maple (*Acer pensylvanicum* L.) dominated the regeneration layer 3 years postharvest in all treatments; however, abundance of intolerant (black cherry; *Prunus serotina* L.) and midtolerant (black and yellow birch; *Betula lenta* L. and *Betula alleghaniensis* Britton.) species was also increased in harvest gaps relative to unharvested controls. Within-gap legacy tree retention hastened sapling development, particularly of intolerant species, highlighting potential tradeoffs in achieving structural and compositional objectives with this gap-based approach.

Keywords: northern hardwoods, uneven-aged management, patch selection, late-successional forests, Massachusetts, coarse woody debris

Prior to European settlement, late-successional forests were a dominant feature in the northern hardwood region of northeastern North America; however, centuries of human land use have reduced these conditions to a small fraction of contemporary landscapes (Davis 1996, D'Amato et al. 2006). Recognition of the value of late-successional forests for sustaining native biodiversity and maintaining critical ecosystem services, such as carbon storage, has led to recommendations for modifying traditional regeneration methods to restore late-successional structural and compositional characteristics to second-growth forests (Keeton 2006, Root et al. 2007). These modifications include the deliberate retention of larger diameter trees and coarse woody debris and the use of group selection and irregular shelterwood approaches to restore the structural and compositional conditions historically present in these forests (Keeton 2006, Hanson et al. 2012, Klingsporn et al. 2012). Given our generally limited experience with these modified approaches, there is a great need for empirical studies examining the impacts of late-successional restoration treatments on the structural and compositional development of second-growth northern hardwoods and long-term growth and yield (cf. Saunders and Arseneault 2013).

Common objectives related to restoring late-successional forest conditions include increasing the representation of historically important canopy tree species and promoting multicohort age structures (Crow et al. 2002). These objectives relate to the biodiversity benefits presented by compositionally and structural diverse forest stands, as well as the commercial importance of less-tolerant species, such as *Betula alleghaniensis* (Keeton 2006). However, contemporary changes in understory competitive conditions in many northern hardwood forests pose an important obstacle to achieving these objectives (Royo and Carson 2006). These changes include the development of dense understories dominated by a few native shrub and tree species and have been related to alterations in historic disturbance regimes (Nyland et al. 2006a) and increased levels of

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; cubic meters (m^3): 1 m^3 = 35.3 ft^3; hectares (ha): 1 ha = 2.47 ac.

deer herbivory (Horsley et al. 2003). For example, in forests impacted by beech bark disease (caused by the fungi *Nectria* spp., preceded by the beech scale *Cryptococcus fagisuga*), the sapling layer often consists of dense thickets of American beech (*Fagus grandifolia* Ehrh.), advance regeneration creating little opportunity for other species to establish and persist (Nyland et al. 2006a). Similarly, long-term application of single-tree selection has increased the dominance of sugar maple (*Acer saccharum* Marsh.) and American beech in the tree regeneration and canopy layers in many northern hardwood systems presenting a challenge to efforts aimed at restoring intolerant and midtolerant tree species (Nyland et al. 2006a, Webster and Jensen 2007, Bolton and D'Amato 2011). Historic disturbance regimes provided the range of canopy openings necessary for maintaining these species (Webster and Lorimer 2005, Hanson and Lorimer 2007), including large tree-fall gaps ≥ 0.4 – 0.1 ha, whereas harvest gaps created by single-tree removals favor strictly tolerant species.

The application of patch selection methods in which all trees, including understory and midstory individuals, are removed in large harvest gaps (≥ 0.1 ha), has been suggested as a potential strategy for increasing the representation of intolerant and midtolerant species on sites with heavy beech competition (Leak 2003, Nyland et al. 2006b). This uneven-aged method has also proven useful for converting even-aged, second-growth northern hardwoods to uneven-aged structures (Kelty et al. 2003), conditions that better approximate those found in late-successional forests (Leak 1975, D'Amato and Orwig 2008). Nevertheless, our understanding regarding the effectiveness of this approach at recruiting intolerant and midtolerant species and converting age structures is based largely on the long-term studies at the Bartlett Experimental Forest in New Hampshire (Leak 1999, 2003), limiting extrapolation to other portions of the northern hardwood region. Moreover, little is known regarding how the retention of coarse woody debris or legacy trees to meet late-successional structural objectives will impact regeneration development.

This study sought to address these key information gaps by examining the regeneration and structural responses of second-growth northern hardwoods in western Massachusetts to patch selection and structural retention treatments. Specific objectives included: (1) quantifying the impacts of structural retention treatments on abundance of postharvest coarse woody debris and development of within-gap legacy trees and (2) evaluating initial (3-year) regeneration responses of intolerant and midtolerant tree species to patch-selection treatments.

Methods

Study Area

This study was conducted within an 80 year-old, second-growth northern hardwood forest on family forestland in the Berkshire Hills of western Massachusetts (N 42.4, W −72.9). Soils within this area are sandy loams derived from glacial till and are somewhat excessively drained (Scanu 1995). Terrain is gently sloping to moderately steep (3–15%) with elevations ranging from 390 to 450 m above sea level. This region has a humid, continental climate with average annual precipitation ranging from 116.2 to 129.5 cm and mean monthly temperatures from −7.7° C in January to 22.2° C in July (NCDC 2006). The site index for sugar maple on the site was 18.3 m at 50 years. There was no history of harvesting in these second-growth areas prior to the onset of the study.

Forest composition of the study area was dominated by American beech, sugar maple, and red maple (*Acer rubrum* L.) and preharvest basal areas ranged from 22.5–35.4 m^2ha^{-1} across the study area. Other common, less abundant overstory species included white ash (*Fraxinus americana* L.), black cherry (*Prunus serotina* Ehrh.), black birch (*Betula lenta* L.), white pine (*Pinus strobus* L.), and big-tooth (*Populus grandidentata* Michx.) and quaking (*Populus tremuloides* Michx.) aspen. Preharvest sapling layers were uniformly dense across the study area (660 – 2,700 stems ha^{-1}) with American beech constituting the primary sapling species (291–2,260 stems ha^{-1}). Other species present in the sapling layer included striped (*Acer pensylvanicum* L.), sugar, and red maple. There were no significant differences in preharvest sapling densities between treatment areas ($F = 2.03$, $P = 0.1798$).

Experimental Design

In winter 2007–2008 a series of patch selection treatments was replicated four times in a randomized, complete block design with blocking based on spatial location. Each block was 4 ha and contained the following treatments: patch selection with no retention (PNR), patch selection with legacy-tree retention (PLR), patch selection with downed woody debris retention (PDR), and an untreated control (CON). All patch selection treatments consisted of a 0.12 ha harvest gap in which all understory saplings and midstory and overstory trees were removed. Harvest gaps and an equally sized plot in CON areas served as the experimental unit in our analyses. An unharvested buffer of ≥ 100 m was placed around each gap to eliminate edge effects from other patches. For the PLR treatments, 4 – 7 codominant or dominant legacy trees were retained within each harvest gap, with preference given to canopy species other than beech or sugar maple, where possible. Total legacy-tree basal area ranged from 4.1– 6.1 m^2 ha^{-1} for this treatment and the primary species retained were white ash, black cherry, yellow birch (*Betula alleghaniensis* Britton), and white pine. The PDR treatment consisted of the deliberate felling and leaving of all overstory trees within a given harvest patch. In contrast, a 5–10 cull individuals were deliberately felled and retained within the other harvest treatments (PNR and PLR) to represent a downed coarse woody debris (CWD) enhancement strategy that may be more operationally and economically feasible. Harvests occurred under frozen, snow-covered conditions, resulting in low levels of incidental scarification across harvest gaps (<10 – 15% of area).

Measurements

A single, 0.12 ha circular plot was established in each treatment area in the summer prior to harvesting and used for measuring vegetation and structural conditions. As such, our evaluations of structural and regeneration responses to each treatment are restricted to the gap- versus stand-level. For the patch selection-based treatments (PNR, PLR, and PDR) harvests were implemented such that patches were centered on the plot, whereas CON plots were randomly located within unharvested portions of a given block. Each harvest gap and control plot was measured in summer 2011 to assess the 3-year response of tree regeneration, legacy trees, and downed CWD to the patch selection treatments. To ensure adequate representation of gap environments, two transects were laid out across the gaps oriented in subcardinal directions (NE, NW, SE, SW) and extended 6.2 m beyond the gap border. Along each transect, 18, 1 m^2 plots were systematically located 2.1 m apart and used for measuring tree regeneration. Data collected from plots beyond the gap border were not included in this study. Within each 1 m^2 subplot, all seedlings (individuals < 1.34 m in height) were tallied by species. All saplings within the 0.12 ha plot (individuals ≥ 1.34 m in height and < 10 cm dbh) were tallied by species. In addition, all legacy trees within the gaps (trees ≥ 10 cm dbh in control plots) were measured for dbh and species. The condition of legacy trees was also noted (i.e., living, dead, snapped, blown down).

The abundance of downed CWD was measured using the line intersect method (Harmon and Sexton 1996) using the same transects established for the 1 m^2 tree regeneration subplots. For this method, the diameter of each piece of CWD ≥ 10 cm in diameter and ≥ 1 m in length encountered along transects was measured, identified to species (where possible), and assigned to a decay class. Decay classes were defined according to Fraver et al. (2002) as: Class I (wood is sound, bark intact, smaller- to medium-sized branches present); Class II (wood is sound to partially rotten, branch stubs firmly attached with only larger stubs present, some bark slippage); Class III (wood is substantially rotten, branch stubs easily pulled from softwood species, wood texture is soft and compacts when wet); or decay Class IV (wood is mostly rotten, branch stubs rotted down to log surface, bark no longer attached or absent [except *Betula* spp.], log is oval or flattened in shape).

Statistical Analyses

The effect of patch selection treatments on tree seedling and sapling densities and the volume of CWD were examined using a mixed model analysis of variance (ANOVA) in which a block was treated as a random effect and treatment was treated as a fixed effect, following the SAS MIXED Procedure (SAS version 9.1, SAS Institute, Inc. 2004). In cases in which the overall model was significant, Tukey's multiple comparison procedure was used to test for differences between patch selection treatments. For all ANOVAs, residuals were checked for normality (Kolmogorov–Smirnov test) and homogeneity of variances (Levene test) and data transformed as necessary. Distributions of downed coarse woody debris piece sizes were compared between treatments using Kolmogorov–Smirnov tests. Legacy-tree mortality rates were calculated as

$$1 - [1 - (M_1/N_0)]^{1/t} \qquad (1)$$

where M_1 is the total number of trees that died during the sampling period, N_0 is the total number of live legacy trees at the beginning of the sampling period, and t is the number of years between sampling periods (Sheil and May 1996).

Multivariate tests for differences in the composition of the tree regeneration layer (seedlings and saplings) between treatments were conducted using multiresponse permutation procedures (MRPP) in PC-ORD version 5.13 (McCune and Mefford 2006). MRPP is a nonparametric, randomization-based multivariate test of differences between groups that compares the plots within a priori groups to a random allocation of plots (McCune and Grace 2002). Sørensen distances were used to calculate average within-group distances for MRPP. Indicator species analysis (Dufrêne and Legendre 1997) was used to describe how well certain tree species differentiated between gap treatments.

Table 1. Average total tree seedling and sapling densities for canopy species and downed woody debris volumes (± 1 SE) across patch selection treatments.

Treatment[a]	Downed woody debris volume (m^3ha^{-1})	Seedling density ($stems^{-1}m^2$)	Sapling density ($stems^{-1}ha$)
CON	35.9 ± 8.5^{a}	1.2 ± 0.3^{a}	$2{,}122 \pm 373^{a}$
PNR	130.6 ± 35.0^{ab}	7.7 ± 2.8^{b}	$3{,}902 \pm 1{,}164^{a}$
PLR	203.1 ± 35.8^{bc}	5.3 ± 3.3^{ab}	742 ± 234^{b}
PDR	332.2 ± 53.9^{c}	4.1 ± 0.6^{ab}	1647 ± 367^{ab}

Downed woody debris represents logs > 10 cm in diameter and 1 m in length, seedlings are individuals < 1.34 m in height, and saplings are individuals > 1.34 m in height and < 10 cm dbh. Means with different letters are significantly different at alpha = 0.05.

[a] CON, untreated control; PNR, patch selection with no retention; PLR, patch selection with legacy tree retention; PDR, patch selection with downed woody debris retention.

Nonmetric multidimensional scaling (NMS; McCune and Grace 2002) was used to graphically display and interpret compositional differences within the tree regeneration layer among treatments after 3 years. This and other ordination techniques are useful for summarizing community data and highlighting patterns in regeneration composition related to particular treatments or environmental conditions. As was the case for MRPP, NMS used Sørensen distances to calculate a distance matrix for the 16 treatment blocks. To reduce noise in the data set, species with fewer than three occurrences were removed from the data matrices (McCune and Grace 2002). The "slow-and-thorough" autopilot mode of NMS in PC-ORD was used to generate solutions. This procedure determines the optimal ordination solution by stepping down in dimensionality from a six-axis to one-axis solution using 40 runs performed on real data followed by 50 Monte Carlo runs using random data (McCune and Mefford 2006). Optimal dimensionality was based on the number of dimensions with the lowest stress (i.e., smallest departure from monotonicity in the relationship between distance in the original space and distance in the reduced ordination space, McCune and Grace 2002). Relationships between tree species abundance and NMS axis scores were explored using Kendall's tau statistic (SAS version 9.1, SAS Institute, Inc. 2004). For all analyses, a P-value of 0.05 or less was defined as statistically significant.

Results

CWD and Legacy Tree Responses

As expected, the greatest volume of downed CWD was within the PDR treatment, which had a significantly greater volume of downed wood than the CON and PNR treatments (Table 1). There was no difference in downed CWD volume between the PDR and PLR, PLR and PNR, or PNR and CON treatments. The size distribution of downed woody debris, as quantified by intercept diameter, did not differ between any of the treatments (data not shown). The annual mortality rate of retained legacy trees was quite low over the 3-year study period (1.7%) with only one of the 20 trees dying; a 34 cm sugar maple that was snapped by an ice storm. Individual legacy tree diameter growth rate ranged from 0.2–1.0 cm yr^{-1} with gap-level legacy tree basal area growth rates averaging 0.03 ± 0.01 $m^2ha^{-1}yr^{-1}$.

Seedling and Sapling Responses

Seedling densities were significantly affected by patch selection ($F_{3,12} = 3.82$, $P = 0.048$), with PNR having a significantly greater seedling density than CON plots (7.7 ± 2.8 versus 1.2 ± 0.3 $stems^{-1}m^2$, respectively; Table 1). There was no difference in seedling densities between any other treatments. Sapling densities were also significantly different between patch selection treatments ($F_{3,12} = 7.56$, $P = 0.008$), with the PLR treatment having lower

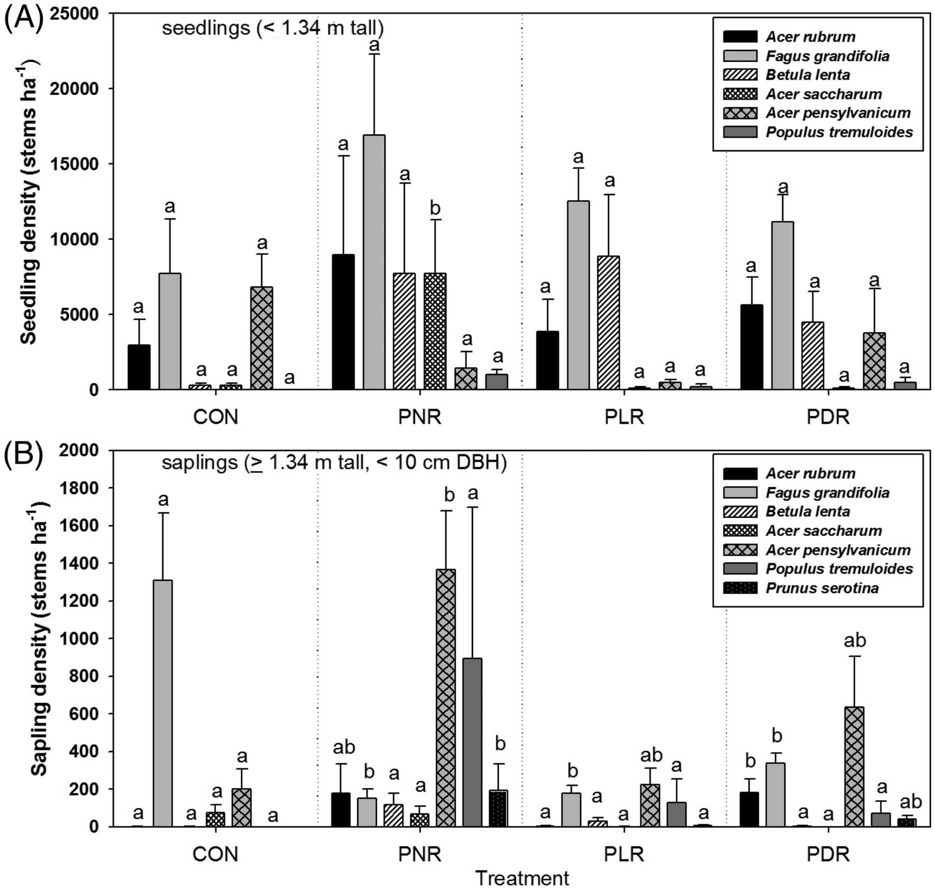

Figure 1. (A) Tree seedling and (B) sapling densities of most common tree species across patch selection treatments within second-growth northern hardwoods in western Massachusetts. CON, untreated control; PNR, patch selection with no retention; PLR, patch selection with legacy tree retention; PDR, patch selection with downed woody debris retention. Error bars represent one standard error and means with different values are significantly different at alpha = 0.05.

densities than the PNR and CON treatments (Table 1). Overall, the density of different tree species within the seedling layer did not differ among treatments, with the exception of sugar maple, which was significantly more abundant within the PNR treatment relative to all other treatments (Figure 1). Within the sapling layer, there were several species that were more abundant within a given treatment or group of treatments. Beech sapling densities were significantly greater in the CON plots relative to all other treatments. Red maple sapling densities were significantly greater in the PDR treatment relative to the CON and PLR treatments, whereas there was no difference in densities of this species in the PNR treatment relative to all other treatments. Black cherry sapling densities were significantly higher in the PNR treatment relative to those found in the CON and PLR treatments, with no difference between PNR and PDR treatments for this species. Striped maple densities were greater in the PNR treatment relative to the controls and similar to the PLR and PDR treatments.

Distinct tree regeneration species assemblages corresponded to several patch selection treatments three years following treatment application (MRPP $A = 0.08$; $P = 0.011$). In particular, pairwise comparisons of regeneration composition between treatments indicated that CON plots differed from PNR and PLR treatments, whereas there was no difference between the PNR, PLR, and PDR treatments. Only two tree species were identified as significant indicators of a given treatment (per Indicator Species Analyses), with sugar maple ($P = 0.003$) and trembling aspen ($P = 0.042$), both as indicators for the PNR treatment.

The differences in composition of the tree regeneration layer between treatments was also illustrated by the general separation of points for several treatments in the ordination of tree regeneration (Figure 2), which explained 61.5% of the variation in the raw data (NMS ordination, final stress = 10.46, final instability = 0.0,00,001). Most of the variation in tree regeneration among treatments was explained by Axis 1 (31.9%), which represented a gradient of disturbance severity ranging from untreated CON plots in the negative portion of Axis 1 to the PNR treatment in the positive portion. Correlations of species with this axis indicated there was greater abundance of striped maple ($\tau = -0.38$) within plots located in the negative portion of Axis 1 and a greater abundance of trembling aspen ($\tau = 0.43$) within plots in the positive portion.

The distribution of treatment plots along Axis 2, which explained 29.6% of the variation, generally ranged from patch selection treatments incorporating late-successional structures (PDR and PLR) in the negative portion of Axis 2 to treatments with little deliberate retention (PNR) or harvesting (CON) in the positive portion (Figure 2). Plots within PDR and PLR treatments tended to have greater amounts of yellow birch and black birch, as there was a significant negative correlation between the abundance of these species and Axis 2 ($\tau = -0.59$ and -0.37).

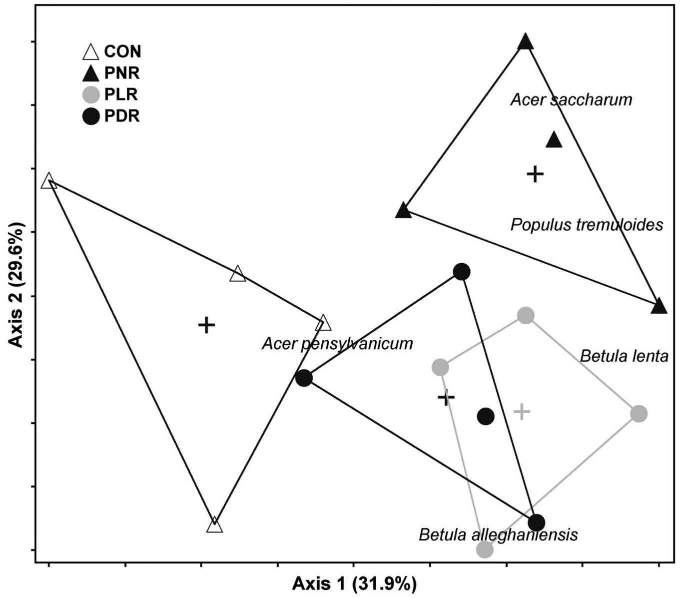

Figure 2. NMS ordination of tree regeneration composition 3 years after the application of each patch selection treatment. CON, untreated control; PNR, patch selection with no retention; PLR, patch selection with legacy tree retention; PDR, patch selection with downed woody debris retention. Species listed are significantly correlated (Kendall's tau, $P < 0.05$) with either Axis 1 or 2 and their location within ordination space is based on weighted averaging scores.

Sugar maple was more abundant within plots in the positive portion of Axis 2 ($\tau = 0.39$).

Discussion

The active restoration of late-successional structural and compositional conditions to second-growth forests represents a relatively new application of silvicultural tools and approaches. To date, much of the work examining these approaches has focused either on stand structural changes in response to structural retention/enhancement treatments (Keeton 2006) or regeneration patterns following natural disturbance-based harvest openings (Arseneault et al. 2011, Bolton and D'Amato 2011). Given that many ownerships may desire achievement of both of these objectives (i.e., late-successional structural conditions and increased tree species diversity; D'Amato and Catanzaro 2007) within the same areas, evaluations of the influence of structural retention/enhancement on regeneration responses in harvest gaps can be useful to gauge their compatibility. Although based on a relatively short posttreatment period, results of this work indicate that benefits associated with structural retention need to be considered within context of potential tradeoffs related to regeneration abundance and composition.

CWD and Legacy Tree Responses

A commonly identified structural difference between old-growth and second-growth northern hardwood forests is the larger volumes of downed CWD found in old-growth stands (Goodburn and Lorimer 1998, McGee et al. 1999). Intuitively, our treatments that deliberately felled and retained downed overstory trees within harvest gaps elevated CWD volumes well above ambient levels found in unharvested control stands. However, this magnitude of CWD enhancement needs to be placed in the context of the scale of our sampling and the operational constraints posed by legacy trees. In particular, average CWD volumes in the PDR treatment were 115–160% higher than those documented for old-growth northern hardwood forests in the region (Burrascano et al. 2013) and reflect the targeted sampling of harvest gaps in our study versus a broader survey of forest stand conditions as is typically done for quantifying CWD levels in old growth. Nevertheless, these CWD volumes are consistent with those documented for localized accumulations of CWD following microbursts and other gap-forming mortality events in the region (Schoonmaker 1992, D'Amato et al. 2008) and indicate that such treatments can be used to provide localized pulses of CWD within stands, particularly in places containing higher concentrations of cull or lower value species.

Solely felling and leaving cull individuals in harvest gaps served to augment volumes of CWD to levels within the range of variation documented for old-growth northern hardwood stands (Burrascano et al. 2013), as is evident by the elevated CWD volumes in the PNR and PLR treatments (Table 1). The higher volumes of CWD in the PLR versus PNR treatments may reflect the operational difficulties associated with extracting felled trees within harvest gaps containing legacy trees (Kluender and Stokes 1994), which potentially led to more trees being felled and left in PLR treatments, particularly in these relatively low-value stands. Given the general prevalence of unacceptable growing stock in family forest and other ownerships in the northeastern region (Munsell et al. 2007), these findings suggest that deliberate felling of these individuals may serve as an effective way to restore late-successional downed CWD levels while also improving the quality of residual stands. While more sophisticated and ecologically based approaches, including pulling down individual trees may also achieve these goals (Keeton 2006), felling of culls represents a practical approach easily implemented on many family forest ownerships. Note this work only focused on downed CWD and additional measures, such as girdling overstory trees, would be needed to restore standing dead tree components to those stands. In addition, deadwood inputs were restricted to the harvest gaps and felling of culls in matrix areas between gaps will be necessary to restore conditions at the stand-level.

The retention of legacy trees has become a common component of ecologically based silvicultural systems and is also included in site-level guidelines for many states (Gustafsson et al. 2012). Traditionally, legacy-tree retention has been primarily applied as a modification of even-aged regeneration methods (e.g., clearcutting with reserves, irregular shelterwoods); however, recent work in northern hardwood systems is highlighting the value of applying this approach within group selection openings to meet biodiversity conservation, structural restoration, and regeneration goals (Keeton 2006, Shields et al. 2007, 2008). The low annual rates of mortality of legacy trees observed in this study (1.7%) are very similar to those documented in other work examining within-gap legacy retention (1.2%; Klingsporn et al. 2012) and suggest these structural features will continue to influence within gap development and structural conditions over extended periods.

Seedling and Sapling Responses

A primary objective related to the use of patch selection treatments is the recruitment of a new cohort containing intolerant and midtolerant species in forests currently dominated by shade-tolerant species (Kelty et al. 2003). The initial regeneration responses observed in the PNR, PLR, and PDR treatments suggest that patch selection was effective at increasing seedling and sapling densities of several intolerant and midtolerant species absent from unharvested areas, including black cherry, trembling aspen, black birch, and yellow birch (Figures 1 and 2). Nevertheless, the densities of these species alone rarely exceeded accepted minimum seedling densities for commercial species (12,500 individuals per ha; Nyland 2007) and the more-tolerant beech, sugar maple, red maple, and striped maple still comprised on average over 70–80% of all seedlings and over 60–90% of all saplings across patch selection treatments. These patterns are consistent with trends observed 3 years following patch selection in second-growth northern hardwoods in New Hampshire, where striped maple, sugar maple, red maple, and beech dominated most areas (Marquis 1965). Long-term measurements of similar stands indicated these trends may be transient, as yellow and paper birch dominated the center of patch selection harvests after 47 years (Leak 2003), despite representing $< 20\%$ of stems on less disturbed seedbeds (Marquis 1965). Given these findings, future monitoring of the openings created in this study will be critical for assessing the proportion of intolerant and midtolerant species that ultimately ascend to canopy positions, particularly in light of the abundant striped maple in these areas, a species known to inhibit regeneration in northern hardwood forests (Nyland et al. 2006a). In addition, the use of deliberate soil scarification may be necessary to increase the representation of light-seeded species, including yellow birch, in patch selection harvests (Marquis 1965).

Structural retention also influenced regeneration development, particularly legacy tree retention, which retarded height growth of regeneration, as evident in the lower overall sapling densities and black cherry sapling densities in the PLR treatment. This pattern is consistent with work examining seedling development in other variable-retention harvest systems (e.g., Mitchell et al. 2007) and underscores the potential tradeoff between regeneration development and structural diversity in retention-based systems. This is a particularly important consideration where objectives include restoring intolerant and midtolerant species as lateral crown growth of gap border and legacy trees may reduce effective gap area over time (Klingsporn et al. 2012) and limit opportunities for canopy recruitment of species less tolerant of shade. Such dynamics may necessitate the progressive expansion of gap openings in subsequent harvests and may argue for the use of irregular shelterwood systems as opposed to selection-based systems if within-gap structural retention and the restoration of intolerant and midtolerant species are long-term management objectives (Raymond et al. 2009).

Conclusions

Forest management objectives related to increasing levels of compositional and structural complexity are becoming increasingly common in response to concerns regarding biodiversity conservation and forest adaptation potential. This study was limited to a short period following treatment application (i.e., 3 years); however, initial results indicate that structural retention/enhancement treatments, including deliberate downed log creation and legacy tree retention, can restore aspects of late-successional structure to gaps within second-growth northern hardwood systems. Similarly, early patterns of seedling recruitment in the harvest gaps we examined support the assertion that patch selection can increase the initial densities of intolerant and midtolerant species in sugar maple and American-beech-dominated stands. Longer-term monitoring of these species will be critical to determine if initial establishment trends are transient or if these less-tolerant species ultimately become canopy tree species in these systems. Relatedly, within-gap legacy tree retention reduces the amount of light available to less-tolerant species and may be restricting sapling growth in these areas and could prevent canopy ascension of less-tolerant species relative to American beech and sugar maple. As such, the application of structural retention treatments needs to be considered within the context of regeneration goals and may be better suited for larger gap openings or irregular shelterwood systems if objectives include restoring late-successional structure and intolerant and midtolerant canopy species.

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