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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
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 thickers 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 m²ha⁻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 PNR 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 m²ha⁻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 m² 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 m² 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 m² 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

\[ 1 - [1 - (M_t/N_0)]^{1/t} \]  

where \( M_t \) 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 (Dufrène and Legendre 1997) was used to describe how well certain tree species differentiated between gap treatments.

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 raw 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; an 8-cm diameter, 3.82-ft-tall, 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 the PLR treatment, which had a significantly greater volume of downed wood than the CON and PNR treatments (Table 1). There was no difference in downed wood between the CON and PNR treatments or between any of the treatments (data not shown).

**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 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 seedling and sapling densities (Table 1).
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 treat-
ment or group of treatments. Beech sapling densities were signifi-
cantly greater in the CON plots relative to all other treatments. Red
maple sapling densities were significantly greater in the PDR treat-
ment relative to the CON and PLR treatments, whereas there was
no difference in densities of this species in the PNR treatment rela-
tive to all other treatments. Black cherry sapling densities were sig-
nificantly 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 indi-
cated 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 in-
dicators 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 regen-
eration (Figure 2), which explained 61.5% of the variation in the
raw data (NMS ordination, final stress $= 10.46$, final instabil-
ity $= 0.000,000$). Most of the variation in tree regeneration
among treatments was explained by Axis 1 (31.9%), which rep-
resented a gradient of disturbance severity ranging from un-
treated 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
($r = 0.38$) within plots located in the negative portion of Axis
1 and a greater abundance of trembling aspen ($r = 0.43$) within
plots in the positive portion.

The distribution of treatment plots along Axis 2, which ex-
plained 29.6% of the variation, generally ranged from patch selec-
ttion 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 treat-
ments 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 ($r = -0.59$ and -0.37).
aging scores. Their location within ordination space is based on weighted aver-

unharvested control stands. However, this magnitude of CWD en-
vest gaps elevated CWD volumes well above ambient levels found in
Lorimer 1998, McGee et al. 1999). Intuitively, our treatments that
of downed CWD found in old-growth stands (Goodburn and
and second-growth northern hardwood forests is the larger volumes
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 har-
vest gaps elevated CWD volumes well above ambient levels found in
unharvested control stands. However, this magnitude of CWD en-
hancement needs to be placed in the context of the scale of our

sugar maple was more abundant within plots in the positive
portion of Axis 2 (τ = 0.39).

Discussion

The active restoration of late-successional structural and composi-
tional 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 natu-
ral disturbance-based harvest openings (Arseneault et al. 2011,
Bolton and D’Amato 2011). Given that many ownerships may de-
sire 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 in-
fluence of structural retention/enhancement on regeneration re-
sponses 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 primary objective related to the use of patch selection treat-
ments 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

Figure 2. NMS ordination of tree regeneration composition 3
years after the application of each patch selection treatment. CON,
ut 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 aver-
aging scores.

Seedling and Sapling Responses

A primary objective related to the use of patch selection treat-
ments is the recruitment of a new cohort containing intolerant and
midtolerant species in forests currently dominated by shade-tolerant
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observed in the PNR, PLR, and PDR treatments suggest that patch
selection was effective at increasing seedling and sapling densities of

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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.

Literature Cited


