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## First decadal response to treatment in a disturbance-based silviculture experiment in Maine

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### ABSTRACT

Disturbance-based silvicultural systems generally seek to promote complex stand structures that are consistent with temporal and spatial patterns of natural disturbance while allowing for the sustainable harvest of timber. Gap-based harvesting systems are commonly used within this framework because they can be designed to approximate the frequencies and spatial patterns of a wide array of disturbance regimes. Patterns in stand-level growth, sapling recruitment and regeneration response were examined for one such gap-based system, the Acadian Forest Ecosystem Research Program (AFERP) in central Maine, that was designed to emulate the annual 1% disturbance frequency typical of the northeastern United States and Canada. A decade after treatment, stand-level differences in basal area growth and density between two gap-based treatments and an unharvested control were not statistically significant, largely due to low replication, but within-stand growth and regeneration responses differed strongly by spatial position relative to harvest gaps. Regeneration of shade-tolerant and intolerant species increased regardless of gap size, likely a response to increasing light availability from canopy openings due to harvesting and mortality. Further, there was evidence of gap size effects on sapling recruitment as large gaps (>1000 m<sup>2</sup>) favored the growth and survival of mid-successional species such as red maple and white pine, while small gaps (<1000 m<sup>2</sup>) favored late-succession species such as eastern hemlock and spruce. Overstorey growth rates also differed by both species and position relative to harvest gaps with most species growing best in gaps and better along gap edges than in adjacent forest. Notably, overstorey growth rates for white pine were not influenced by spatial position. These results suggest harvest gaps may have significant growth and regeneration impacts in adjacent, yet unharvested areas, which could lead to profound differences in forest development over the rotation. Obviously, longer-term studies of gap-based systems are needed to more clearly elucidate these responses.

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### 1. Introduction

During recent decades, there has been a shift away from traditional production forestry focused on high-yield and low-cost wood production (Seymour et al., 2006), to “disturbance-based” or “ecological” forestry, where conservation of biodiversity and maintenance or improvement of ecosystem resilience, health, and natural processes are also major foci of silvicultural activities (Angelstam, 1998; Armstrong, 1999; Attiwill, 1994; Franklin and Forman, 1987; Lindenmayer et al., 2006; Pickett et al., 1997). Disturbance-based silviculture relies on the underlying premise that forest species have adapted to one or more dominant natural disturbance regimes and that more closely emulating these disturbances could maintain a diverse and resilient ecosystem (Landres et al., 1999; Long, 2009; McRae et al., 2001; Swanson et al.,

1994). To implement these systems, characteristics of local disturbance regimes must be quantified in terms of frequency, intensity, size, and other characteristics (Seymour and Hunter, 1999). The goal of these systems is to produce spatial patterns and residual forest characteristics similar to those arising from natural disturbances, and consequently maintain ecosystem processes and biodiversity within their range of natural variability (Raymond et al., 2009). This goal can be difficult to achieve as residual forest characteristics after a natural disturbance event are often quite different from those characteristics in forests harvested with silvicultural systems designed to emulate those disturbances (Long, 2009).

There are few long-term studies of the growth impacts with the application of natural disturbance-based systems. For example, gap-based harvesting regimes can be designed to approximate natural disturbance frequency and spatial pattern for many temperate forest types. Studies of these systems have investigated the effects of gap-based harvesting on the flora, fauna, and processes of forest

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ecosystems largely within or immediately adjacent to the gaps (Coates, 2002; Falk et al., 2008; Fraver et al., 2002; Koivula and Niemelä, 2003; Schumann et al., 2003; York et al., 2003, 2004). While these studies have provided valuable insights regarding the functioning of these forest types under gap conditions, there has been a paucity of research on overstory trees beyond those with canopies immediately adjacent to harvest gaps. In these systems, these matrix effects can be just as influential as gap responses to the long-term ecological and economical viability of the treatments.

Results from studies of high-contrast forest ecotones (Brothers and Spingarn, 1992; Euskirchen et al., 2001; Fraver, 1994) can be difficult to compare to gradients from canopy openings into adjacent forests as environmental differences along these gradients can be relatively subtle (Cadenasso et al., 2003; Fahey and Puettmann, 2008). Some simulation studies have suggested canopy gap influences on growth and regeneration responses should extend into the adjacent forest beyond the vertical projections of canopy openings (Dube et al., 2001; Menard et al., 2002), but there is a dearth of experimental evidence in this regard. For example, McDonald and Urban (2004) suggested effects of canopy gaps on tree growth did not extend 5 m beyond the gap edge, while Fahey and Puettmann (2008) suggested canopy gap influence on understorey communities did not extend 2 m beyond the edge of 0.4 ha gaps and none at all for 0.1 ha gaps. However, there still exists a strong need for ecological analysis of forest edges in gap-based systems to better elucidate their effects on forest structure and composition and to develop and calibrate forest growth models to better simulate growth responses of gap-based, and other more complicated disturbance-based silvicultural systems.

In this study, we investigated the effect of canopy openings using two gap-based silvicultural systems based on natural disturbance patterns of northeastern North America. Specifically, we assessed harvest-induced changes in forest structure, regeneration and sapling recruitment in both canopy openings and the adjacent forest matrix using data from the Acadian Forest Ecosystem Research Program (AFERP) in central Maine. We hypothesized that (1) harvests using larger gaps (>1000 m<sup>2</sup>) would promote regeneration and sapling recruitment of mid-successional species while harvests using smaller gaps (<1000 m<sup>2</sup>) would favor late-successional species; and (2) within-stand structural and regenerative responses would be widely variable and differ strongly by position relative to harvest gaps.

## 2. Methods

### 2.1. Study area

The Acadian Forest Ecosystem Research Program is located in the Penobscot Experimental Forest (PEF), situated approximately 15 km north of Bangor, Maine near the towns of Bradley and Eddington (44°51'N, 68°37'N). The PEF is 1,618 ha and part of the Acadian Forest Region, an ecotone between the northern boreal and southern broadleaf forests with a cool and humid climate. The mean annual temperature for nearby Bangor is 6.6 °C, with 48% of 106 cm of normal precipitation falling during the average growing season from May through October (156 days; Adams et al., 2004). The coldest and warmest months are January and July, with average daily temperatures of −7.7 °C, and 20.0 °C, respectively. The soils are derived from glacial till and range from well-drained loams, stony loams and sandy loam ridges, to poorly drained loams and silt loam flat areas, with poorly drained silt and silty clay loams along watercourses and depressions (Brisette, 1996; Saunders and Wagner, 2008).

Vegetation types in the PEF are diverse. Forest canopies are dominated by conifers, including red, white and black spruce

(*Picea rubens* Sarg., *Picea glauca* (Moench) Voss, and *Picea mariana* (Mill.) BSP, respectively), balsam fir (*Abies balsamea* (L.) Mill.); eastern white pine (*Pinus strobus* L.), northern white-cedar (*Thuja occidentalis* L.), and eastern hemlock (*Tsuga canadensis* (L.) Carrière). Deciduous species generally consist of sugar and red maple (*Acer saccharum* Marsh. and *Acer rubrum* L., respectively); paper and gray birch (*Betula papyrifera* Marsh. and *Betula populifolia* Marsh., respectively), and trembling and large tooth aspen (*Populus tremuloides* Michx. and *Populus grandidentata* Michx., respectively) (Saunders and Wagner, 2008).

A variety of natural disturbance agents are present in the Acadian Forest Region. Within coniferous and mixed deciduous-coniferous forest types, the drivers of stand dynamics are insect epidemics, primarily spruce budworm (*Choristoneura fumiferana* Clem.) that selectively kills most balsam fir and a significant proportion of spruce species on a 35–70 year return interval (Fraver et al., 2007; Lorimer and White, 2003). Windthrow, senescence, and other disturbances create canopy gaps (<400 m<sup>2</sup>) through the death of individual and small groups of trees, affecting 0.5–2.0% of the forest annually (Fraver and White, 2005; Runkle, 1982); these gaps are rarely distributed spatially and temporally uniformly across the landscape (D'Amato and Orwig, 2008; Foster, 1988; Fraver et al., 2007). Ice storms and microburst wind events occur more rarely, hypothesized 0.5–2.0 times in a given area per century, but on larger spatial scales, sometimes creating canopy gaps up to 5000 m<sup>2</sup> (Hanson and Lorimer, 2007; North and Keeton, 2008). Large-scale, stand-replacing events, such as hurricanes and fire, occur only rarely with return intervals of 250+ and 800+ years, respectively (Cogbill, 1985; Lorimer and White, 2003; Seymour et al., 2002).

### 2.2. Study design

The Acadian Forest Ecosystem Research Program (AFERP) was established in 1995 to develop and test alternative silvicultural systems that are based on regional disturbance ecology, can maintain the economic advantages of even-aged methods, and provide many of the structural features found in uneven-aged stands (Saunders and Wagner, 2005). The AFERP's overarching goal is to create a silvicultural system that is capable of producing a sustained yield of forest products while creating stand structural conditions that are consistent with the range of variation for natural disturbances occurring in the region. The AFERP study includes three treatments consisting of an experimental control and two expanding-gap systems based on the German "Femelshlag" system:

**Large-gap:** This is an extended group shelterwood with reserves, with 20% of the area removed on a 10-year cutting cycle. Target initial gap sizes are 1000–2000 m<sup>2</sup> (actual: 320–2170 m<sup>2</sup> on an expanded gap basis) and the regeneration period for any gap or expansion is 10 years. In addition, presalvage harvesting outside these gaps is allowed in the first cutting cycle, largely to capture value from smaller, but overmature, short-lived species such as balsam fir and paper birch that commonly die from butt rot and other pathogens in these forest types. With these presalvage harvests, care is taken as to not create canopy gaps that would stimulate regeneration. All removals occur during the first half of the 100-year rotation; the stand then "rests" for the second 50 years. This system encourages species with intermediate shade tolerance and maintains a stand at a mid-successional status.

**Small-gap:** This is "expanding" group selection with 10% area removal on a 10-year cutting cycle. Target initial gap sizes are 500–1000 m<sup>2</sup> (actual: 110–1290 m<sup>2</sup>) and the regeneration period for any gap or expansion is 20 years. This is achieved by having 50% of the gaps within the stand on alternate expansion/cutting cycles (i.e., two gap cohorts). There is no "rest" period, nor is there

presalvage harvesting of the matrix allowed. This system encourages shade-tolerant species and accelerates stands to a late-successional status.

In both systems, reserve trees of long-lived (e.g., white pine) or uncommon species (e.g., red oak, and large sugar maple) are retained in the regenerating gaps at a basal area density of 3.7 m<sup>2</sup> ha<sup>-1</sup>, approximately 10% of the preharvest stocking. Low-quality, short-lived species are targeted for removals; these include aspen, birch, fir and red maple.

Unlike many ecologically based, multi-aged silvicultural systems that emphasize a size-based target residual stand structure (North and Keeton, 2008), the AFERP treatments employ an area-based structure which offers many practical advantages for implementation (Seymour, 2005). Further, these treatments approximate the spatial (500–2000 m<sup>2</sup>) and temporal (1% annual, area-based disturbance rate) scale of natural disturbances of the region; the AFERP treatments fall very near the 100% natural disturbance compatibility line, conceptualized by Seymour et al. (2002) and modified by North and Keeton (2008) to include intermediate-scale disturbances. Lastly, the AFERP treatments explicitly include reservation of mature trees and protection of rare species, snags and large down woody debris (Saunders and Wagner, 2005), features that often are lacking using traditional even- and uneven-aged techniques in these forests.

The two expanding gap treatments and an unmanaged control are replicated three times across nine, 8.9–11.3 ha research areas (RA) within irregularly-aged mixed hardwood-conifer sites. Between eight and ten gaps were created within each harvested research area. The design is a randomized complete block, with blocks based on harvest date: replicate 1 harvested in winter 1995–96, replicate 2 in winter 1996–97 and replicate 3 in winter 1997–98. More detailed descriptions of the AFERP's design and inventory systems can be found in Saunders and Wagner (2005) and Saunders et al. (in review).

### 2.3. Data and analysis

The AFERP recently completed its first 10-year cutting cycle, and while it is too early to assess the long-term sustainability and viability of these treatments, there are now sufficient data to quantify the first decadal responses in stand structure, composition, growth and productivity, and evaluate their concurrence with past studies of gap dynamics. Pre-treatment plot measurements were conducted in 1995–97, with post-treatment inventories conducted every five years starting in 2000–02. A nested sampling design was used, with all overstory trees  $\geq 9.5$  cm diameter at breast height (DBH) measured within 0.05 ha circular sample plots and saplings between 1.5 cm and 9.5 cm DBH measured within 0.01 ha circular subplots centered within the overstory plots. Prior to both initial harvest and gap delineation, 20 overstory plots were installed per replicate by randomly selecting locations from intersections of a 50 × 50 m grid overlain on the replicate. A road installed in 1999 accidentally destroyed five plots in the third replicate of the small gap treatment (Table 1); these five plots were used only to estimate initial pre-harvest conditions, and excluded from all post-harvest analysis and comparisons.

Tree regeneration was inventoried with four 1 m<sup>2</sup> quadrats within each overstory plot. Stocking was estimated by overstory plot as the proportion of stocked quadrats (e.g., three stocked quadrats out of four = 75% stocked). This estimate represents a stocking target of 2500 evenly distributed trees ha<sup>-1</sup>. Changes in stocking levels were obtained by comparing the last completed inventory to the initial pre-harvest inventory.

Tree heights were not measured in the overstory or sapling inventories, and were instead estimated using the Curtis–Arney equation (Arney, 1985; Curtis, 1967) with species-specific coeffi-

**Table 1**  
Initial plot distribution by treatment replicate and overstory class.

Treatment and replicate	Overstory class		
	Matrix	Edge	Gap
<i>Large-gap</i>			
1	9	4	7
2	10	8	2
3	9	9	2
<i>Small-gap</i>			
1	16	3	1
2	12	5	3
3 <sup>a</sup>	15	4	1
<i>Control</i>			
1	20	–	–
2	20	–	–
3	20	–	–

<sup>a</sup> Before the post-harvest inventory in 2000, five matrix plots were accidentally destroyed while constructing a road to an adjacent unit.

cients used by the Northeast Variant of the Forest Vegetation Simulator (Dixon and Keyser, 2008). Correspondingly, tree volumes were estimated using Honer's metric total volume equation (Honer, 1967; Honer et al., 1983).

To test the hypothesis that growth and regeneration response depends on proximity to gaps, plots were categorized into three overstory classes based on their distance relative to harvest gaps. Plots located completely within initial harvest gap boundaries were designated as "Gap" plots. Plots outside the expanded gap boundaries but within 18 m of the boundary were designated as "Edge" plots. On a practical side, the width of this zone represents the initial average height of codominant/dominant trees across all research areas; it also roughly represents the width of the planned expansions around several of the gaps (i.e., one tree height). Furthermore, Olson (2009) reported that the mean range of spatial autocorrelation for tree regeneration density and canopy openness in six of the AFERP's research areas was from 14–18 m and 18–25 m, respectively, with higher regeneration density generally associated with higher light levels in gaps. All other plots were designated "Matrix" plots (Table 1).

Immediate post-treatment RA characteristics were summarized at the plot level by comparing subsets of the pre-treatment RA inventories to the full inventory. In other words, plot summaries of all trees not marked as being harvested or missing during the first post-harvest inventory (i.e., assumed harvest) were compared to the initial pre-treatment RA inventory (i.e., all trees) to determine changes in density, basal area, and volume due to harvest.

Importance values (IV) were calculated to summarize changes in forest composition. Overstory and sapling trees IVs were the sums of relative dominance (%), relative frequency (%), and relative density (%), while seedling IVs were the sums of relative frequency and relative density. Importance values for each size category were scaled to integer values ranging from 0 to 100.

Testing of treatment-level hypotheses was conducted using RAs as experimental units. Analysis of variance (ANOVA) was used to evaluate differences in pre-treatment structural characteristics among RAs and post-treatment differences in matrix residual tree diameter growth rates. Unrestricted, non-directional, paired *t*-tests were used to assess the weight of evidence for differences in pre- and post-treatment structural characteristics among treatments (Saville, 1990; Goodman, 1998). Testing of class-level hypotheses were conducted using plots as experimental units, which were pooled across treatments if no significant difference in residual tree diameter growth rates between treatments were detected using two-sample *t*-tests. Two-sample *t*-tests using Welch–Satterthwaite degrees of freedom approximation for unequal sample sizes and inhomogeneous variance (Kutner et al., 2004)

were also used to assess differences in residual tree diameter growth rates between overstory classes after plots were pooled.

Formal tests of parametric statistical assumptions were not performed due to low treatment replication. However, assumptions of normality were likely satisfied as the response variables are sample means of plots in each experimental unit ( $n = 15$  and  $20$ ). All data analysis and testing were done using the stats package in R (R Development Core Team, 2010).

Lastly, many large-scale management studies have inventories designs that are used predominately for aspatial comparison of treatments over long time frames (Puettmann et al., 2009); the AFERP study is no exception. This analysis was designed to detect evidence for an edge-effect phenomenon that could help describe differences in forest structure and composition; these effects could then be investigated in other high-power studies. Therefore, maximizing power was also a priority with the small sample sizes, as any Type I errors that may occur would be likely shown false in future high-power experiments. Therefore, we used unrestricted  $t$ -tests and an apriori significance level of 0.10 to minimize Type II error (Saville, 1990; Stewart-Oaten, 1995).

### 3. Results

#### 3.1. Initial conditions and harvest impacts

No differences in volume, basal area, or density between treatments were found among research areas (RA) prior to treatment ( $p = 0.861$ ,  $p = 0.954$ ,  $p = 0.829$ , respectively), giving strong statistical evidence that treatment comparisons are real and not an artifact of pre-harvest structural differences. RA volume, basal area and tree density averaged  $283.6 \pm 10.4 \text{ m}^3 \text{ ha}^{-1}$ ,  $37.6 \pm 1.1 \text{ m}^2 \text{ ha}^{-1}$  and  $2404 \pm 138 \text{ trees ha}^{-1}$ , respectively ( $\pm 1$  standard error from the mean). Stands were composed primarily of red maple, hemlock, and balsam fir. Balsam fir was generally present in the highest densities, with quadratic mean DBH (qDBH) varying between 4.5 and 12.1 cm. Red maple and hemlock were fewer and larger, with qDBH varying from 13.9 to 21.2 cm and 12.8 to 23.2 cm, respectively. White pine, a species that often is emergent in these forest types, was present in all RAs in the form of relatively few ( $32 \text{ trees ha}^{-1}$ ), large trees varying between 31.7 and 49.1 cm qDBH.

Harvest treatments decreased volume, basal area and tree density by  $11.3 \pm 5.1\%$  ( $\pm 1$  standard error relative to pre-treatment mean),  $13.4 \pm 5.2\%$ , and  $21.6 \pm 3.8\%$ , respectively, in the small-gap system, and by  $27.2 \pm 1.5\%$ ,  $30.7 \pm 1.9\%$ , and  $39.7 \pm 3.9\%$ , respec-

tively, in the large-gap system (Table 2). These changes were all quite spatially variable and varied strongly by species (Table 3), with the two gap treatments having differing effects, largely due to the presalvage harvesting of the matrix in the large-gap treatment. Volume and basal area decreased within the edge overstory class more strongly in the large-gap treatment,  $24.8 \pm 3.9\%$  and  $28.8 \pm 4.6\%$ , respectively, than in the small-gap treatment,  $18.0 \pm 0.7\%$  and  $20.1 \pm 0.4\%$ , respectively. Further, the matrix overstory class of the large-gap treatment showed strong changes in volume and basal area ( $-22.0 \pm 1.5\%$  and  $-24.9 \pm 1.2\%$ , respectively) relative to the small-gap and control treatments, which did not differ (e.g., changes in volume of  $-3.6 \pm 5.6\%$  and  $-4.0 \pm 2.3\%$ , respectively).

#### 3.2. Treatment responses

Slight differences in growth rates among the treatments were observed. Mean basal area increment was higher in the large-gap ( $0.27 \pm 0.05 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ ) than small-gap treatment ( $-0.05 \pm 0.12 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ ;  $p = 0.046$ ). There was no difference ( $p > 0.10$ ) in mean basal area increment between either gap treatment and the control due to the high variability observed ( $-0.09 \pm 0.25 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ ). Mean volume growth averaged  $2.62 \pm 0.25 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ,  $0.80 \pm 0.86 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  and  $0.66 \pm 1.70 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , for the large-gap, small-gap and control treatments, respectively; this did not differ among treatments ( $p > 0.10$  for all comparisons).

#### 3.3. Overstory response

Across all treatments, the matrix class was initially very similar in terms of species importance values (IVs) and did not differ over time (Table 4). Post-treatment, fir IVs slightly increased while spruce IVs slightly decreased in the gap and edge classes of the large-gap treatment, while the opposite occurred in those classes within the small-gap treatment. Red maple and hemlock IVs were generally the greatest in absolute terms across all treatments and overstory classes, but while red maple remained relatively equivalent, post-treatment hemlock values slightly decreased in the gap class of both treatments. In the small-gap treatment, white pine and spruce were generally not harvested, which partially explains their slight increases in IVs in the gap class. In both treatments, IVs of shade intolerant species, such as birch and aspen, slightly decreased in the edge class and slightly increased in the gap class. Few of these relationships, however, were significant ( $p > 0.10$ ) due to the high variability among replicates.

Species diameter growth rates between the edge and gap classes did not differ ( $p = 0.17$ – $0.89$ ), but some differences in aspen, balsam fir, and red maple growth rates in the matrix class among treatments were observed. Diameter growth rates of aspen in the large-gap treatment were greater than those observed in the small-gap treatment ( $p = 0.093$ ), and both gap treatments were greater than the control ( $p = 0.001$  and  $0.061$ , respectively). Red maple diameter growth rates between the large-gap and control treatments were not different ( $p = 0.382$ ), but both were greater than the small-gap treatment ( $p = 0.002$  and  $0.002$ , respectively). Balsam fir growth rates in the large-gap treatment were greater than the control ( $p = 0.033$ ), but neither differed from the small-gap treatment ( $p = 0.251$  and  $0.326$ , respectively). The increased growth rates of aspen and red maple in the matrix class may be the result of reduced competitive pressure from the large mortality events that occurred in the small-gap and control treatments, as well as the presalvage harvesting efforts in the large-gap treatment. The salvage harvest in the large-gap treatment could also explain the increased growth rates of balsam fir in this treatment, because it likely targeted slower growing fir showing signs of

**Table 2**

Estimated harvest impacts on volume, basal area and tree density in each replicate by treatment, as derived from differences between initial and first remeasurement values and corrected for growth during the intervening 5-year period. Estimates for the control treatment include nothing but mortality, but estimates for the large-gap and small-gap treatments may include some natural mortality in this period.

Treatment and replicate	Volume ( $\text{m}^3 \text{ ha}^{-1}$ )	Basal area ( $\text{m}^2 \text{ ha}^{-1}$ )	Density (trees $\text{ha}^{-1}$ )
<i>Large-gap</i>			
1	-84.2	-12.4	-670.0
2	-72.7	-11.7	-1130.0
3	-70.2	-10.0	-1223.0
<i>Small-gap</i>			
1	-23.8	-4.1	-339.0
2	-59.1	-8.8	-533.0
3	-12.0	-2.2	-645.7
<i>Control</i>			
1	-9.1	-1.5	-103.0
2	-24.7	-3.8	-384.0
3	-1.7	-0.4	-69.0



**Table 3**Initial and post-treatment basal area ( $\text{m}^2 \text{ha}^{-1}$ ), and percent change (%) by overstory class for all trees  $>15$  cm diameter at breast height.

Treatment	Species	Matrix			Edge			Gap		
		Init.	Post.	%	Init.	Post.	%	Init.	Post.	%
<i>Large-gap</i>										
	White pine	3.74	3.52	-6	6.52	6.27	-4	2.20	2.20	0
	Red maple	5.34	3.46	-35	5.39	3.35	-38	7.60	2.16	-72
	Spruce	2.77	2.64	-4	2.55	2.39	-6	1.15	1.06	-8
	Fir	1.31	0.32	-76	1.73	0.17	-90	1.34	0.06	-95
	Hemlock	11.09	9.54	-14	7.55	6.10	-19	3.98	2.93	-26
	Other Spp. <sup>a</sup>	11.90	10.33	-13	7.23	4.37	-40	6.48	1.80	-72
	Total	36.15	29.81	-18	30.97	22.65	-27	22.75	10.21	-55
<i>Small-gap</i>										
	White pine	4.94	5.41	9	3.25	3.25	0	2.54	2.54	0
	Red maple	7.17	6.82	-5	6.08	4.28	-30	12.54	6.04	-52
	Spruce	1.82	1.75	-4	1.42	1.21	-15	0.82	0.82	0
	Fir	1.84	1.30	-29	1.66	0.83	-50	2.06	0.07	-96
	Hemlock	6.22	6.12	-2	5.48	5.05	-8	3.81	1.05	-72
	Other Spp. <sup>a</sup>	8.85	8.46	-4	8.81	7.42	-16	6.79	3.47	-49
	Total	30.84	29.86	-3	26.70	22.04	-17	28.56	13.99	-51
<i>Control</i>										
	White pine	5.52	5.51	0						
	Red maple	5.10	5.03	-1						
	Spruce	1.16	1.01	-13						
	Fir	1.16	0.95	-18						
	Hemlock	8.50	8.34	-2						
	Other Spp. <sup>a</sup>	9.78	9.34	-4						
	Total	31.22	30.18	-3						

<sup>a</sup> The "Other Spp." category consists of the following species: ash, aspen, birch, cedar, red oak, red pine, sugar maple and other non merchantable species.

**Table 4**Summary of changes in scaled importance values by treatment, overstory class and species. Combinations in bold italics are significant at  $\alpha = 0.10$ .

Treatment and species	Overstory			Sapling			Seedling		
	Matrix	Edge	Gap	Matrix	Edge	Gap	Matrix	Edge	Gap
<i>Large gap</i>									
White pine	0	0	0	0	+++	++	(+++)	(+++)	(+++)
Red maple	0	0	0	0	++	+++	+	0	0
Spruce	0	-	--	0	0	0	0	0	0
Fir	0	+	+	0	0	--	--	--	--
Hemlock	0	0	--	0	0	--	(++)	(++)	++
<i>Small gap</i>									
White pine	0	0	++	0	+	+++	+++	+++	+
Red maple	0	+	0	0	--	+++	+	++	-
Spruce	0	(+)	++	0	0	+++	0	++	0
Fir	-	-	(+)	-	0	--	--	--	-
Hemlock	0	<b>0</b>	-	0	+	+++	(++)	++	+++

$\Delta$  IV: 0-5 = 0; 5-10 = - | +; 10-20 = -- | ++; >20 = --- | +++.

imminent mortality for removal, which would increase the mean diameter growth rate.

To assess overstory class effects on diameter growth rates, plots were pooled across treatments and summarized (Table 5). White pine diameter growth rates across all treatments were not different (all  $p > 0.600$ ), likely because it was usually emergent and would not benefit from canopy openings. Some species, such as red maple and balsam fir, exhibited significantly different growth rates in all overstory classes and diameter growth rates were gen-

**Table 5**Mean diameter growth rate ( $\text{cm yr}^{-1}$ ) for selected species by overstory class ( $\pm 1$  standard error). Within species, overstory classes with the same letter do not have significantly different growth rates at  $\alpha = 0.10$  and using two-sample  $t$ -tests.

Species	Matrix	Edge	Gap
White pine	0.51 $\pm$ 0.04 <sup>a</sup>	0.52 $\pm$ 0.04 <sup>a</sup>	0.57 $\pm$ 0.10 <sup>a</sup>
Red maple	0.16 $\pm$ 0.00 <sup>a</sup>	0.20 $\pm$ 0.01 <sup>b</sup>	0.27 $\pm$ 0.03 <sup>c</sup>
Spruce	0.15 $\pm$ 0.01 <sup>a</sup>	0.24 $\pm$ 0.03 <sup>b</sup>	0.26 $\pm$ 0.08 <sup>ab</sup>
Fir	0.11 $\pm$ 0.00 <sup>a</sup>	0.16 $\pm$ 0.01 <sup>b</sup>	0.25 $\pm$ 0.02 <sup>c</sup>
Hemlock	0.26 $\pm$ 0.01 <sup>a</sup>	0.33 $\pm$ 0.03 <sup>b</sup>	0.42 $\pm$ 0.06 <sup>b</sup>

erally greatest in the gap class, followed by the edge, then matrix class. Hemlock and spruce growth rates in the edge class were significantly greater than matrix growth rates, but did not differ from those observed in the gap class.

### 3.4. Sapling recruitment

There were no strong differences between pre- and post-treatment sapling and small-tree species composition across all overstory classes and treatments (Table 6). This result was largely driven by the ubiquitously high stem densities of balsam fir present throughout the study areas. Importance values were more sensitive, however, likely because they incorporated both relative density and relative dominance; IVs suggested that sapling recruitment has differed slightly among treatments (Table 4). Most of the observed changes were within the edge and gap classes, with differences in species responses presumably driven by gap size. For example, IVs of white pine increased in the edges of the large gap treatment more dramatically than in the small gap treatment likely from increased regeneration and growth of existing saplings

**Table 6**  
Mean decadal change in percent of total saplings by species ( $\pm 1$  standard error) from post-harvest condition and as separated by treatment and overstory class. Species totals may not sum to 100% due to rounding errors.

Treatment and species	Matrix			Edge			Gap		
	Post-harvest	Final	Change	Post-harvest	Final	Change	Post-harvest	Final	Change
<i>Large-gap</i>									
White pine	0 $\pm$ 0	1 $\pm$ 1	0 $\pm$ 0	0 $\pm$ 0	3 $\pm$ 3	3 $\pm$ 3	0 $\pm$ 0	1 $\pm$ 1	1 $\pm$ 1
Red maple	11 $\pm$ 2	9 $\pm$ 3	-1 $\pm$ 3	11 $\pm$ 3	27 $\pm$ 17	16 $\pm$ 17	9 $\pm$ 3	42 $\pm$ 8	32 $\pm$ 9
Spruce	3 $\pm$ 1	3 $\pm$ 1	-1 $\pm$ 0	1 $\pm$ 0	1 $\pm$ 1	0 $\pm$ 1	2 $\pm$ 1	1 $\pm$ 1	-1 $\pm$ 1
Fir	62 $\pm$ 19	68 $\pm$ 13	7 $\pm$ 6	55 $\pm$ 26	52 $\pm$ 26	-3 $\pm$ 0	58 $\pm$ 26	37 $\pm$ 13	-21 $\pm$ 16
Hemlock	16 $\pm$ 12	15 $\pm$ 10	-1 $\pm$ 3	27 $\pm$ 23	14 $\pm$ 9	-12 $\pm$ 14	23 $\pm$ 18	9 $\pm$ 5	-14 $\pm$ 14
Other Spp. <sup>a</sup>	6 $\pm$ 2	2 $\pm$ 0	-4 $\pm$ 2	4 $\pm$ 1	1 $\pm$ 1	-3 $\pm$ 0	5 $\pm$ 3	10 $\pm$ 8	4 $\pm$ 5
<i>Small-gap</i>									
White pine	0 $\pm$ 0	0 $\pm$ 0	0 $\pm$ 0	1 $\pm$ 1	1 $\pm$ 1	0 $\pm$ 0	0 $\pm$ 0	3 $\pm$ 2	3 $\pm$ 2
Spruce	3 $\pm$ 2	4 $\pm$ 2	1 $\pm$ 1	5 $\pm$ 4	2 $\pm$ 1	-4 $\pm$ 2	0 $\pm$ 0	1 $\pm$ 1	1 $\pm$ 1
Red maple	14 $\pm$ 4	12 $\pm$ 4	-2 $\pm$ 1	8 $\pm$ 4	5 $\pm$ 1	-3 $\pm$ 3	5 $\pm$ 3	32 $\pm$ 17	27 $\pm$ 18
Fir	48 $\pm$ 7	48 $\pm$ 11	0 $\pm$ 8	52 $\pm$ 8	62 $\pm$ 7	10 $\pm$ 9	91 $\pm$ 5	58 $\pm$ 15	-33 $\pm$ 18
Hemlock	24 $\pm$ 2	27 $\pm$ 5	3 $\pm$ 6	17 $\pm$ 12	18 $\pm$ 5	0 $\pm$ 11	1 $\pm$ 1	4 $\pm$ 3	3 $\pm$ 4
Other Spp. <sup>a</sup>	8 $\pm$ 5	7 $\pm$ 5	-2 $\pm$ 1	15 $\pm$ 6	12 $\pm$ 5	-3 $\pm$ 3	0 $\pm$ 0	2 $\pm$ 2	2 $\pm$ 2
<i>Control</i>									
White pine	0 $\pm$ 0	2 $\pm$ 2	1 $\pm$ 1	-	-	-	-	-	-
Red maple	9 $\pm$ 3	5 $\pm$ 1	-3 $\pm$ 2	-	-	-	-	-	-
Spruce	1 $\pm$ 1	1 $\pm$ 0	0 $\pm$ 0	-	-	-	-	-	-
Fir	69 $\pm$ 2	64 $\pm$ 4	-6 $\pm$ 6	-	-	-	-	-	-
Hemlock	10 $\pm$ 2	22 $\pm$ 5	12 $\pm$ 7	-	-	-	-	-	-
Other Spp. <sup>a</sup>	7 $\pm$ 1	4 $\pm$ 1	-2 $\pm$ 0	-	-	-	-	-	-

<sup>a</sup> The "Other Spp." category consists of the following species: ash, aspen, birch, cedar, red oak, red pine, sugar maple, and other non merchantable species.

in the large gap edge environment. Red maple, on the other hand, increased only in large gap edge, presumably due to its sprouting ability in these high light environments, but decreased in the small gap treatment as its relative density decreased through competition with more shade tolerant species.

No differences in balsam fir's relative density response were observed in the matrix or edge classes of both treatments in comparison to the control, but its IVs declined in the gap class ( $p = 0.360$  and  $p = 0.042$ , for the large- and small-gap, respectively), primarily due to decreases in relative density caused by red maple's positive response to the harvest. Regardless, it continued to be the dominant species in all overstory classes of both treatments, followed by red maple and hemlock (Table 6).

### 3.5. Regeneration stocking and composition

Balsam fir, hemlock and red maple were the primary species regenerating across all overstory classes and treatments (Table 7).

High stocking levels for balsam fir and red maple were observed across all overstory classes in all treatments, both initially and a decade post-treatment. The consistent decrease in balsam fir IV's across overstory classes was primarily due to the influx of regeneration that occurred post-treatment, as opposed to a decline in stocking or density (Table 4). Red maple replaced balsam fir as the most dominant species post-treatment, particularly in the gap class, likely because of its copious sprouting ability (Table 7). Both treatments produced similar, and sometimes significant, improvements in hemlock stocking levels and IVs for the large- and small-gap treatments (Tables 4 and 7). White pine stocking and relative density increased under both treatments, but were slightly greater in the large-gap treatment (Table 7), leading to significant increases in IVs across all overstory classes in that treatment (Table 4). Stocking levels and relative frequencies of some shade intolerant species, such as aspen and birch, also increased slightly across all overstory classes and all treatments (data not shown).

**Table 7**  
Mean initial (year 0), final (year 10), and decadal change of species regeneration stocking percent ( $\pm 1$  standard error) as separated by treatment and overstory class.

Treatment and species	Matrix			Edge			Gap		
	Initial	Final	Change	Initial	Final	Change	Initial	Final	Change
<i>Large-gap</i>									
White pine	4 $\pm$ 4	75 $\pm$ 10	71 $\pm$ 8	7 $\pm$ 7	80 $\pm$ 5	72 $\pm$ 3	21 $\pm$ 15	100 $\pm$ 0	79 $\pm$ 15
Red maple	93 $\pm$ 4	90 $\pm$ 10	-3 $\pm$ 9	100 $\pm$ 0	92 $\pm$ 8	-8 $\pm$ 8	100 $\pm$ 0	100 $\pm$ 0	0 $\pm$ 0
Spruce	22 $\pm$ 10	32 $\pm$ 11	10 $\pm$ 7	23 $\pm$ 10	27 $\pm$ 9	4 $\pm$ 7	14 $\pm$ 5	14 $\pm$ 5	0 $\pm$ 0
Fir	97 $\pm$ 3	86 $\pm$ 7	-11 $\pm$ 6	92 $\pm$ 8	79 $\pm$ 15	-13 $\pm$ 7	100 $\pm$ 0	100 $\pm$ 0	0 $\pm$ 0
Hemlock	43 $\pm$ 12	64 $\pm$ 13	21 $\pm$ 5	32 $\pm$ 11	63 $\pm$ 19	31 $\pm$ 13	43 $\pm$ 30	62 $\pm$ 31	19 $\pm$ 19
<i>Small-gap</i>									
White pine	27 $\pm$ 11	62 $\pm$ 11	35 $\pm$ 6	15 $\pm$ 8	43 $\pm$ 23	28 $\pm$ 17	78 $\pm$ 22	89 $\pm$ 11	11 $\pm$ 11
Red maple	78 $\pm$ 11	89 $\pm$ 11	10 $\pm$ 10	78 $\pm$ 22	100 $\pm$ 0	22 $\pm$ 22	100 $\pm$ 0	100 $\pm$ 0	0 $\pm$ 0
Spruce	16 $\pm$ 6	17 $\pm$ 6	1 $\pm$ 4	50 $\pm$ 17	75 $\pm$ 25	25 $\pm$ 8	33 $\pm$ 33	33 $\pm$ 33	0 $\pm$ 0
Fir	81 $\pm$ 12	75 $\pm$ 13	-6 $\pm$ 10	100 $\pm$ 0	93 $\pm$ 7	-7 $\pm$ 7	89 $\pm$ 11	78 $\pm$ 22	-11 $\pm$ 11
Hemlock	36 $\pm$ 11	62 $\pm$ 18	26 $\pm$ 6	37 $\pm$ 15	54 $\pm$ 14	17 $\pm$ 27	0 $\pm$ 0	67 $\pm$ 33	67 $\pm$ 33
<i>Control</i>									
White pine	17 $\pm$ 6	52 $\pm$ 2	35 $\pm$ 6	-	-	-	-	-	-
Red maple	87 $\pm$ 7	82 $\pm$ 8	-5 $\pm$ 5	-	-	-	-	-	-
Spruce	15 $\pm$ 5	5 $\pm$ 2	-10 $\pm$ 4	-	-	-	-	-	-
Fir	90 $\pm$ 8	90 $\pm$ 3	0 $\pm$ 6	-	-	-	-	-	-
Hemlock	50 $\pm$ 3	52 $\pm$ 12	2 $\pm$ 15	-	-	-	-	-	-

## 4. Discussion

### 4.1. Treatment effects

Differences in residual tree diameter growth rates among overstory classes and treatments were both difficult to detect due to small sample sizes for many species by overstory class by treatment combinations. This limitation was generally not a concern for the more prevalent species such as balsam fir, red maple, spruce, white pine, and hemlock. Despite the relatively small proportion of gap-affected area within each treatment and the relatively short period of observation, we detected differences in diameter growth among surviving trees in the matrix and gap classes. These growth increases were likely due to competitive release from harvested trees, and were similar to those reported for selection systems (Forget et al., 2007; Pedersen and Howard, 2004). As the experiment progresses and future entries expand initial gaps and affect a greater proportion of plots, differences in structural responses among treatments and overstory classes may become more pronounced.

### 4.2. Regeneration patterns

The observed regeneration and sapling recruitment trends were consistent with the silvics of Acadian species and our knowledge of transient dynamics following canopy disturbances in that region. The Acadian forest is characterized by an abundance of advance regeneration consisting of hemlock, red spruce, and fir (Brissette, 1996; Brissette and Kenefic, 2000). Observed regeneration in gaps created by both treatments consisted primarily of red maple sprouts and advance balsam fir seedlings and saplings, both of which are known to respond well to release and exhibit rapid growth (USDA, 1990; Weaver et al., 2009).

The large-gap treatment increased white pine regeneration stocking levels and relative density, but also increased the presence of its primary competitors, namely balsam fir and red maple (Burgess and Wetzell, 2002). Maintaining shade intolerant and mid-tolerant species has been observed under a range of canopy openings comparable to those created within the AFERP (Dale et al., 1995; Leak, 1999; Webster and Lorimer, 2005). Competition control will likely be required in the future if white pine recruitment is desired, as white pine is known for regenerating in small canopy gaps, but failing to survive to the sapling stage due to suppression (Carleton et al., 1996; Leak et al., 1995).

Similarly, the small-gap treatment appeared to improve conditions for hemlock regeneration. However, the range of canopy opening sizes was greater than what has been reported for sustaining hemlock populations. Primary competitors for hemlock, such as intolerant birch and aspen, increased in importance values within the edge and gap classes. Sporadic small-openings in mature canopy (Brissette and Kenefic, 2000) not exceeding  $\frac{3}{4}$ –1 times the height of adjacent residual trees (Goerlich and Nyland, 2000) have been recommended to favor hemlock regeneration. While shade-tolerant species can achieve greater basal area increment post-harvest relative to mid-tolerant species under certain selection systems (Jones et al., 2009), Webster and Lorimer (2002) found that yellow birch (*Betula alleghaniensis* Britton) superseded eastern hemlock in relative biomass as opening size increased. Moores et al. (2007) suggested that for overstory densities  $<30 \text{ m}^2 \text{ ha}^{-1}$  there is no understory light condition within Acadian forests that favors the growth of red spruce and hemlock over balsam fir of the same height. Therefore, it is not clear whether hemlock will be able to maintain a competitive position in these harvested stands.

### 4.3. Promoting mid- and late-successional composition

It is difficult to assess the capability of these expanding-gap systems to successfully establish desirable regeneration and accelerate stands towards mid- and late-successional conditions without further intervention. The replicates in the AFERP are currently in a mid-successional state and, so far, the gap sizes implemented in the AFERP do not appear to promote regeneration of their respective target species. Our findings partially support the hypothesis that harvests using larger gaps ( $>1000 \text{ m}^2$ ) will promote regeneration and sapling recruitment of mid-successional species while harvests using smaller gaps ( $<1000 \text{ m}^2$ ) will favor late-successional species. Both treatments generally increased the regeneration of shade-tolerant and intolerant species indiscriminately (Table 4), which is likely due to an increase in light availability and not treatment-specific effects. The gap harvests appeared to have had a strong effect on forest composition at the sapling level, where the greatest changes in importance values were for the targeted species. We have yet to observe how these treatments will likely affect the long-term growth and survival of saplings over time, and determine if additional silvicultural treatments will be required to achieve the respective forest compositions the treatments were designed to maintain. Ultimately, the need for additional intervention will depend on how much of a competitive advantage desired species can garner prior to the expansion harvests. Given the range of canopy opening sizes implemented at the AFERP, controlling competitors of the slower-growing, shade tolerant species will likely be required in the larger canopy openings to ensure their establishment and survival.

It should also be noted that while initial canopy opening sizes may be appropriate for regenerating intermediate and shade tolerant species, changes in gap characteristics during subsequent expansions and over the entire length of the rotation may affect forest growth and composition. For example, given these hybrid systems are based on constant area removals during each cutting cycle, and every successive entry expands existing gaps, expansion gap “widths” would become progressively narrower without careful planning. The AFERP, for example, uses asymmetrical gap expansions to help compensate for this.

### 4.4. Interim results as a predictor of future conditions

The novel aspects of these two expanding gap-based silvicultural systems have yet to be observed, because the initial harvest entries in themselves are essentially entries in a group-selection system modified to include structural retention within the group. Consequently, the structural and compositional responses observed to date are functions of differences in initial gap size between treatments, and not the more novel aspects of these systems, such as gap-expansion, which have yet to occur. Nonetheless, our interim results support the hypothesis that within-stand structural and regenerative responses differ by position relative to harvest gaps. Both systems showed signs of effecting some change on seedling species composition in terms of improvements in regeneration of desired species, as well as noticeably affecting species composition and growth in the forest matrix surrounding canopy openings. These results suggest canopy gaps may have a biologically significant impact on the adjacent forest that extends into the matrix beyond the edges of the canopy boundaries. In a similar but higher-power study, York and Battles (2008) found that gaps 0.1–1.0 ha in size within a Sierra Nevada mixed conifer forest increased radial growth of tree significantly within 10 m of gap edge, regardless of species or orientation relative to gap. In mixed conifer forests of the Northeast, however, there would likely be orientation differences in growth as light, and not moisture, is a more limiting factor to growth; Schofield (2003) hinted at these

differences in a study of the AFERP understory vegetation within the gaps. Regardless, more research is required to better understand canopy gap effects on the adjacent forest condition. From a practical perspective, a better understanding of these effects will allow for better design and implementation of disturbance-based and other silviculture systems that try to take advantage of the increased growth both in and around gaps. This further has direct impacts of forest growth and yield modeling in that disturbance-based systems in much eastern North America are gap-based and not uniformly applied across a stand, resulting in differing proportions of forest conditions (matrix/edge/gap) over time, with potentially differing dynamics that may not be captured by the a spatial stand- or tree-level model.

#### 4.5. Value of long-term disturbance based silviculture experiments

Long-term, large-scale experiments such as the AFERP (Saunders and Wagner, 2005; Seymour, 2005), the Vermont Forest Ecosystem Management Demonstration Project (FEMDP; Keeton, 2006), the Ouachita Mountains Ecosystem Management Research Project (OMEM; Guldin, 2004), Silvicultural Options for Young-growth Douglas-fir Forests (SOYDF; Curtis et al., 2004), and Silviculture Treatments for Ecosystem Management in the Sayward (STEMS; de Montigny, 2004) are vital to the discussion of sustainable disturbance-based silviculture. Little research has been conducted using spatial and temporal scales appropriate to study and observe the operational implications, economical feasibility, and long-term sustainability of disturbance-based silvicultural systems. Short-term studies can investigate alternate hypotheses with greater statistical power; however, these studies often do not observe anything beyond transient dynamics that can drastically differ from long-term behavior (Tilman, 1989). Consequently, when considered alone, they are generally insufficient to validate these silvicultural approaches as economically viable and capable of sustainably producing both timber and non-timber forest products at either a stand- or forest-level. These long-term experiments are an important complement to short-term studies as they provide a frame of reference against which the validity of hypotheses derived from transient results can be assessed and considered in context, while also yielding insights regarding the operational feasibility and long-term sustainability of these new disturbance-based methods.

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