

Effect of silvicultural gap size on 51 year species recruitment, growth and volume yields in *Quercus* dominated stands of the Northern Cumberland Plateau, USA

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This manuscript seeks to further the understanding of how silvicultural gap size affects stand development and growth patterns among species. The authors studied an experiment established more than 50 years ago in oak (*Quercus* spp.) dominated stands that tested three gap sizes, 0.02 ha, 0.16 ha and 0.46 ha. Statistical analysis addressed stand-level trends associated with tree size, density, and sawtimber volume as well as species recruitment and individual tree growth and volume. Distinct patterns among gap sizes were present in overall structural characteristics including a significant increase in year 51 sawtimber volume with increasing gap size. Data also indicated that conditions present in the different gap sizes had an influence on individual tree size and that the nature of this effect varied among species group. Tree recruitment among the primary species groups, maple (*Acer* spp.), oak and yellow-poplar (*Liriodendron tulipifera* L.), was strongly related to gap size and a notable trend with species shade tolerance was present. Results highlighted how shifting species proportions and changes in tree size associated with different gap sizes can alter important stand characteristics that affect management and forest utility within gap-based silvicultural approaches for upland mixed oak forests in the study region.

Introduction

Forest gaps have been studied in the context of naturally occurring openings resulting from tree mortality and stand disturbance along with silvicultural openings created by patch clearcutting, group selection, or irregular shelterwood methods (Coates and Burton, 1997; Kern et al., 2017). While the mechanisms creating natural vs silvicultural gaps differ, the foundational factors directing the microclimate conditions and associated response by tree regeneration are similar (Coates and Burton, 1997). The two factors most noted to influence the forest microclimate in gaps are the opening size and the forest structural characteristics beyond the gap margin (Canham et al., 1990; Pritchard and Comeau, 2004; Ye and Comeau, 2009). The primary interaction of these two factors, gap size relative to the height of the surrounding forest overstory, drives light availability within circular forest openings and light increases as the ratio between the opening width and surrounding canopy heights becomes larger (Fischer, 1981; Takenaka, 1988; Chen et al., 1993). Not only is total available light altered by this interaction but also the spatial distribution of light with greatest light availability generally observed in centres and northern portions of gaps in the Northern Hemisphere (Gray et al., 2002; Raymond et al., 2006; Prévost and Raymond, 2012).

The importance of microclimate characteristics and patterns in gaps on tree regeneration and recruitment cannot be overstated. Gap size and associated light availability can greatly influence which tree species are able to maintain competitive growth rates (Coates, 2000; York et al., 2004; Powers et al., 2008; de Montigny and Smith, 2017) and hence have a strong influence on forest developmental pathways of gaps. Due to the distribution of light and other microclimatic factors across gaps, spatial variation of tree regeneration and growth rates can also occur based on species physiological adaptations and the environmental conditions within a given locale inside a gap (Gray and Spies, 1996; de Chantal et al., 2003; Raymond et al., 2006; Poznanovic et al., 2014).

Silvicultural practices based upon gap principles are being integrated into the management toolbox for a wide range of forest ecosystems to address traditional and emerging forestry objectives (Coates and Burton, 1997; Arseneault et al., 2011; Kern et al., 2017). Unlike even-aged regeneration systems that treat whole stands uniformly, gap-based systems founded on concepts of irregular silviculture create greater heterogeneity across stands in terms of microclimates and species patterns (O'Hara, 2014). While this heterogeneity is one reason why these approaches are used (Coates and Burton, 1997), it also makes the development of gap-based systems with predictable

outcomes more difficult, especially for forest types with high diversity in species shade tolerance and ecological growth strategy. Kern *et al.* (2017) in their review of gap-based systems stressed the need to understand the linkage between gap size, light availability and species regeneration outcomes, but also noted the complexity of this relationship and how it can be influenced by additional factors like landscape position, animal damage, and competition from native and non-native species.

The existing literature provides a strong basis for understanding many elements critical to the design of gap-based silvicultural practices including gap size-microclimate relationships immediately following gap creation (Takenaka, 1988; Canham *et al.*, 1990; Chen *et al.*, 1993; Gray *et al.*, 2002; Pritchard and Comeau, 2004; Raymond *et al.*, 2006) along with species regeneration and growth patterns during early periods of stand development (Gray and Spies, 1996; Coates, 2000; York *et al.*, 2004; Raymond *et al.*, 2006; Powers *et al.*, 2008; Arseneault *et al.*, 2011; Poznanovic *et al.*, 2014). However, multi-decadal silvicultural gap studies are rare and there is a need to better understand how growth environments created by differing gap size can influence long-term stand development pathways and yield trends through mid-rotation (or later) among species that vary widely in shade tolerance and ecological growth strategy. This manuscript seeks to provide insight into this critical component of gap dynamics in the context of silvicultural practice.

The authors studied a replicated gap size experiment of more than 50 years old in a deciduous broadleaf forest type common to eastern North America, upland mixed oak (*Quercus* spp.). Species occurring within this study location represent an array of shade tolerance characteristics and regeneration strategies providing an example of how growth environments created by varying gap sizes interact with species traits to direct long-term forest composition and yield outcomes at the stand and individual tree levels. In this context, the objectives of this manuscript are to quantify the effects of gap size on (1) stand-level trends associated with tree size, density and sawtimber volume accumulation, and (2) species recruitment trends and individual tree growth and volume.

Methodology

Study description and design

This manuscript utilized a study established in 1960 on the University of Kentucky Robinson Forest (lat. 37.470°, long. -83.130°). The study site was part of a regional harvest opening size study initiated by the USDA Forest Service Central States Forest Experiment Station and sited at five locations across the Central Hardwood Forest Region (Dale *et al.*, 1995). The Robinson Forest study site was within the Northern Cumberland Plateau ecological section of the United States (Cleland *et al.*, 2007). The climate of the region is humid subtropical having an average daily temperature of 1.6–9.1°C in November through March and 14.1–24.1°C in April through October. Annual precipitation averages 122.8 cm. Twenty-seven experimental plots were installed on the upper slope positions of the main ridge separating the two primary watersheds on the Robinson Forest. Plots ranged in elevation from 399 m to 452 m, had moderate to steep slopes (37–66%) and predominantly had a southeastern aspect. Site index among the plots ranged from 17 to 20 m for oaks (Dale *et al.*, 1995).

A completely randomized design among the 27 plots was used to test two main effects, size of harvest opening and site preparation

intensity. Each treatment combination was replicated three times. Previous research evaluating the Robinson Forest opening size study site as well as the other locations from the original regional study sites found that the site preparation treatments had no effect on initial regeneration density and composition (Sander and Clark, 1971) or long-term species composition, stand structure and growth (Dale *et al.*, 1995; Lhotka, 2013). So like these other works, this study pooled the site preparation main effect within the three gap size treatments, circular harvest diameters of 15.2 m (0.02 ha), 45.7 m (0.16 ha) and 76.2 m (0.46 ha). The pooled site preparation treatments included three levels of chemical control of stems <7.6 cm, no chemical control, basal application of 2,4,5 T for all species, basal application of 2,4,5 T for all species except oak and hickory (*Carya* spp.).

Plots were established in the spring of 1960 by harvesting all merchantable trees >30.5 cm dbh whose stems were located within the plot area defined by each gap size treatment. Immediately following the harvest associated with each plot, all non-merchantable trees >30.5 cm dbh were girdled with a gasoline-driven mechanical tree girdler and all trees between 7.6 cm and 30.5 cm dbh were frilled and treated with a solution of 2,4,5, T and No. 2 fuel oil (4% herbicide solution by volume). Establishment records indicated that among gap size treatments an average of 4.5 m² ha⁻¹ basal area were girdled and 7.4 m² ha⁻¹ basal area were frilled and treated with herbicide. While the specific timing of tree mortality following girdling and frill and herbicide treatments was not documented, written observations and photographs in the study records indicated that the treatments were effective at deadening trees within the plots. However, a few large diameter trees with girdling scars were present in the current inventory suggesting a small proportion of trees may have survived the girdling treatment. Following treatment implementation, no further silvicultural operations were carried out within the 51-year study period.

Stand structure and species composition at the time of harvest treatment was not known as a pretreatment overstory inventory was not conducted. Historical information indicated that the Mowbray and Robinson Lumber Company harvested all merchantable timber on Robinson Forest from 1900 to 1920. Therefore, stands that included the experimental plots were likely 40–60 years old at the time of treatment. Based upon the overstory composition observed for the untreated area that surrounds the plots today, the plots were likely oak dominated when treatments were implemented. Immediately following treatment (1960) a regeneration survey was completed. Total seedling density and density by species group did not differ among the gap sizes. Total seedling density across all treatments was 15 831 trees ha⁻¹, while oak, hickory, maple (*Acer* spp.) and yellow-poplar (*Liriodendron tulipifera* L.) species groups had densities of 2 319, 1 545, 1 566 and 421 trees ha⁻¹, respectively (Lhotka, 2013).

Data collection and analysis

In the summer of 2011, the original plot centres were relocated using roadside markers, plot monuments and tree tags installed in 1981 (Hill, 1987). Plot re-measurement was not done using complete enumeration, but through a subplot sampling approach. Gaps with a diameter of 15.2 m (0.02 ha) were assigned one subplot with a radius of 6.7 m. The 0.16 ha and 0.46 ha gaps were assigned five subplots. The first subplot was located at the original plot centre, the second subplot was positioned directly upslope, the third subplot to the right across the slope aspect, the fourth subplot was directly downslope from plot centre and the fifth subplot to the left of the plot centre along the slope aspect (Figure 1). Due to the different areas within plots, subplots in the 0.16 ha and 0.46 ha gaps had a radius of 6.7 m and 11.4 m, respectively. Subplot size and number were selected so that sampling covered approximately the same percentage of area within gaps regardless of their size.

Within each subplot, species, diameter at breast height (1.4 m above ground level) (dbh) and merchantable height in number of 4.9 m (16 ft) logs was recorded for all live trees ≥ 15.2 cm dbh. Of the 27 original plots, one 0.02 ha gap was excluded from re-measurement because it was inadvertently harvested after study establishment (Hill, 1987). A second 0.02 ha gap was excluded because it contained a residual overstory tree from prior to the 1960 treatment implementation; girdling scars were clearly observed on the bole of this large (45 cm) tree. It was thought prudent to exclude this plot from data collection because of the disproportionate effect this residual tree likely had on tree development in such a small plot. The 25 remeasured plots included seven replicates of the 0.02 ha gap treatment and nine replications each for the 0.16 ha and 0.46 ha gaps.

Tree data collected among the experimental plots were used to quantify the effect of gap size on forest structure conditions, individual tree size characteristics and species proportions. Data were aggregated to determine tree density (ha^{-1}), basal area ($\text{m}^2 \text{ha}^{-1}$) and quadratic mean diameter (cm) for each plot. Using observed dbh and merchantable height for each tree ≥ 30.5 cm dbh, per tree sawtimber board-foot volume was calculated using the Doyle 78 form class equation presented in Wiant (1986). Board-foot volumes were then converted to m^3 volume using methods outlined in Husch et al. (2002) including an assumption of five board-feet per cubic feet. Total m^3 sawtimber volumes were then calculated on a per ha basis by plot and for the following species groups within each plot, maple (*Acer rubrum* L., *Acer saccharum* Marsh.), oak (*Quercus alba* L., *Quercus coccinea* Muench., *Quercus falcata* Michx., *Quercus prinus* L., *Quercus rubra* L., *Quercus velutina* Lamb.) and yellow-poplar. While 30 species were observed across the plots, this manuscript focuses on analysis of these three primary species groups which accounted for 85% of the basal area among gap size treatments. Relative density and mean dbh of all trees and sawtimber-sized trees were determined by species group and plot. Relative density was defined as the proportion of trees ha^{-1} for a given species group to the total trees ha^{-1} . Mean per tree sawtimber volume by species group and plot were also computed.

Analysis of variance (ANOVA) with $\alpha = 0.05$ was used to test the effect of gap size on dependent variables relating to forest structure and individual tree size. Normal Q-Q plots, plots of residuals vs fitted values, and scale-location plots were used to check for heteroscedasticity and non-normality of the residuals. In cases where diagnostic plots indicated

that assumptions of homogeneity of variance and/or normality were not met, data were transformed using the Box-Cox power transformation. Lambda parameters for the Box-Cox power transformations were determined using PROC TRANSREG (SAS Institute Inc., Cary, NC). In all cases, analysis of diagnostic plots indicated that transformed models minimized issues with heteroscedasticity and non-normality of the residuals. To facilitate interpretation, untransformed values are presented in the text and tables. To address statistical testing of proportional data, generalized linear ANOVA models ($\alpha = 0.05$) with a binomial distribution and logit link function (Schabenberger and Pierce, 2002; Zuur et al., 2009) were used to test the effect of gap size on relative density of all trees and sawtimber-sized trees by species group as well as the proportion of sawtimber-sized trees among gap size. *Post hoc* multiple comparisons for all ANOVA models outlined above were done using the Tukey test and $\alpha = 0.05$. All statistical testing was completed using SAS 9.4 (SAS Institute Inc., Cary, NC).

Results

Fifty-one years after treatment, distinct trends were apparent among the three gap sizes tested with regard to overall structural characteristics (Table 1). Both tree density and basal area were significantly greater in the 0.16 ha and 0.46 ha gaps than in the smallest opening (0.02 ha). Average tree diameter as measured by quadratic mean diameter differed among the gap sizes and increased as the gap sizes became larger. By year 51, no sawtimber volume had accrued in the 0.02 ha gaps. Sawtimber volume increased significantly in both the 0.16 ha ($30.2 \text{ m}^3 \text{ha}^{-1}$) and 0.46 ha ($51.2 \text{ m}^3 \text{ha}^{-1}$) gaps. Mean sawtimber volume ha^{-1} was also significantly larger in the 0.46 ha gap than in the intermediate gap size (0.16 ha).

With regard to all trees inventoried in year 51 (i.e. dbh ≥ 15.4 cm), the maple species group accounted for approximately half of the trees per hectare in the smallest gap. Significantly reduced relative densities were present for maple in the two larger gap sizes (Table 2). The highest relative density of oak (0.37) was found in the intermediate gap size; oak relative density did not differ between the 0.02 and 0.46 ha gaps. No yellow-poplar was inventoried in the 0.02 ha gap and significantly increasing

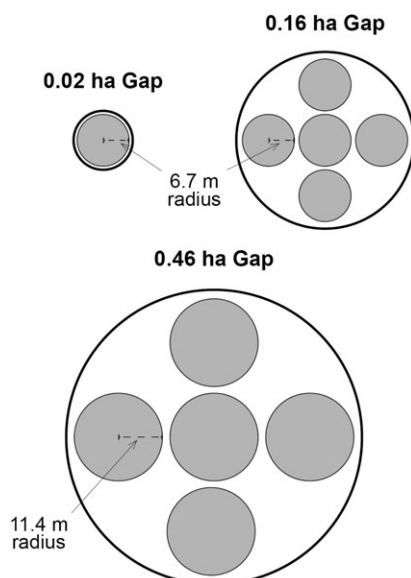


Figure 1 Subplot sampling design for tree inventories by opening size.

Table 1 Mean (\pm standard error) basal area, density, quadratic mean diameter and sawtimber volume by opening size 51 years following gap creation.

Variable	Gap size		
	0.02 ha	0.16 ha	0.46 ha
Density (trees ha^{-1})	191.9a ¹ (± 29.73)	358.5b (± 37.58)	309.7b (± 9.71)
Basal area ($\text{m}^2 \text{ha}^{-1}$)	5.2a (± 0.94)	19.4b (± 1.30)	21.8b (± 0.96)
Quadratic mean diameter (cm)	18.7a (± 0.81)	26.7b (± 1.17)	29.9c (± 0.65)
Sawtimber volume ($\text{m}^3 \text{ha}^{-1}$)	0.0a	30.2b (± 5.78)	51.2c (± 6.42)

¹Means followed by the same letter are not significantly different ($\alpha = 0.05$).

relative densities of this species were present in the 0.16 ha and 0.46 ha gaps (Table 2).

A number of data points indicate that the growth conditions present in the different gap sizes had a notable influence on individual tree size. In addition to a larger quadratic mean diameter with increasing gap size, species group patterns in mean dbh were seen among the data for all trees inventoried (Table 2). Mean dbh for the oak group differed among gap size and increased with opening size from 18.7 cm to 34.2 cm. For yellow-poplar, average dbh did not differ between the two largest gap sizes (31.3 and 32.1 cm, respectively). The maple group's mean dbh was significantly smaller in the 0.02 gap size (18.3 cm), but did not differ between 0.16 ha (23.3 cm) and 0.46 ha gaps (24.6 cm).

The proportion of sawtimber-sized trees (dbh \geq 30.5 cm) differed significantly among the three gap sizes ($P = 0.009$) and

was shown to be 0, 0.24 and 0.36 in the 0.02 ha, 0.16 ha and 0.46 ha gaps, respectively. Among all species, the mean sawtimber volume per individual tree was also significantly larger in the 0.46 ha gap (0.44 m³) than in the 0.16 ha gap (0.34 m³) ($P = 0.022$). Oaks represented about half of sawtimber trees in the 0.16 ha gap and a significantly reduced relative density (0.40) in the 0.46 ha gap (Table 3). The relative density of sawtimber-sized yellow-poplar was significantly larger in the 0.46 ha gap (0.29) than in the 0.16 ha gap (0.20) (Table 3).

Between the two largest gap sizes, the mean dbh and per tree volume of sawtimber trees did not differ for maple or yellow-poplar (Table 3). Sawtimber volume per tree for the oak group was significantly greater in the 0.46 ha gap (0.54 m³) than in the 0.16 ha gap (Table 3). Difference between mean dbh for sawtimber size oaks in the two largest gap sizes (36.3 cm vs 39.8 cm) was not statistically significant ($P = 0.0618$) (Table 3). An apparent shift in merchantable height distribution towards an increase in the number of logs per tree was also present between the 0.16 ha and 0.46 ha gaps for the oak and yellow-poplar groups (Figure 2).

Table 2 Mean (\pm standard error) relative density and dbh for all trees inventoried (i.e. dbh \geq 15.4 cm) by species group.

Variable by species	Gap size		
	0.02 ha	0.16 ha	0.46 ha
Maple			
Relative density ¹	0.50a ² (\pm 0.18)	0.39b (\pm 0.04)	0.42b (\pm 0.06)
Dbh (cm)	18.3a (\pm 1.41)	23.3b (\pm 1.14)	24.6b (\pm 0.56)
Oak			
Relative density	0.21a (\pm 0.15)	0.37b (\pm 0.08)	0.24a (\pm 0.04)
Dbh (cm)	18.7a (\pm 1.40)	28.0b (\pm 1.87)	34.2c (\pm 1.07)
Yellow-poplar			
Relative density	–	0.13a (\pm 0.04)	0.21b (\pm 0.06)
Dbh (cm)	–	31.3a (\pm 2.70)	32.1a (\pm 1.01)

¹Relative density was defined as: $\left(\frac{\text{trees ha}^{-1} \text{ for species group}}{\text{total trees ha}^{-1}}\right)$.

²Means within a species group followed by the same letter are not significantly different ($\alpha = 0.05$).

Discussion

Overall microclimatic conditions of newly formed forest gaps are a function of their size relative to the height of the surrounding overstory (Takenaka, 1988; Chen *et al.*, 1993). Gap size can be practically manipulated through silviculture and increasing gap size yields larger levels of available light across a gap area although this relationship and associated spatial patterning within a gap can be altered by aspect and topographical characteristics (Fischer, 1981; de Chantal *et al.*, 2003; Voicu and Comeau, 2006; Prévost and Raymond, 2012). The gap partitioning hypothesis (Ricklefs, 1977; Denslow, 1980) describes the establishment and growth response of vegetation in relation to the forest microclimate associated with gap size and spatial patterning within gaps. The hypothesis proposes that as microclimatic parameters important to plant growth (most notably

Table 3 Mean (\pm standard error) relative density, dbh and per tree sawtimber volume for sawtimber-sized trees (dbh \geq 30.5 cm) by species group.

Variable by species	Opening size		
	0.02 ha	0.16 ha	0.46 ha
Maple			
Sawtimber relative density ¹	–	0.20a ² (\pm 0.07)	0.23a (\pm 0.06)
Sawtimber dbh (cm)	–	34.3a (\pm 1.32)	33.7a (\pm 0.72)
Sawtimber volume (m ³) per tree	–	0.27a (\pm 0.04)	0.25a (\pm 0.02)
Oak			
Sawtimber relative density	–	0.51a (\pm 0.12)	0.40b (\pm 0.07)
Sawtimber dbh (cm)	–	36.3a (\pm 1.22)	39.9a (\pm 1.28)
Sawtimber volume (m ³) per tree	–	0.34a (\pm 0.04)	0.55b (\pm 0.07)
Yellow-poplar			
Sawtimber relative density	–	0.21a (\pm 0.07)	0.29b (\pm 0.08)
Sawtimber dbh (cm)	–	37.0a (\pm 1.43)	37.3a (\pm 0.92)
Sawtimber volume (m ³) per tree	–	0.44a (\pm 0.06)	0.47a (\pm 0.04)

¹Relative density was defined as: $\left(\frac{\text{trees ha}^{-1} \text{ for species group}}{\text{total trees ha}^{-1}}\right)$.

²Means within a species group followed by the same letter are not significantly different ($\alpha = 0.05$).

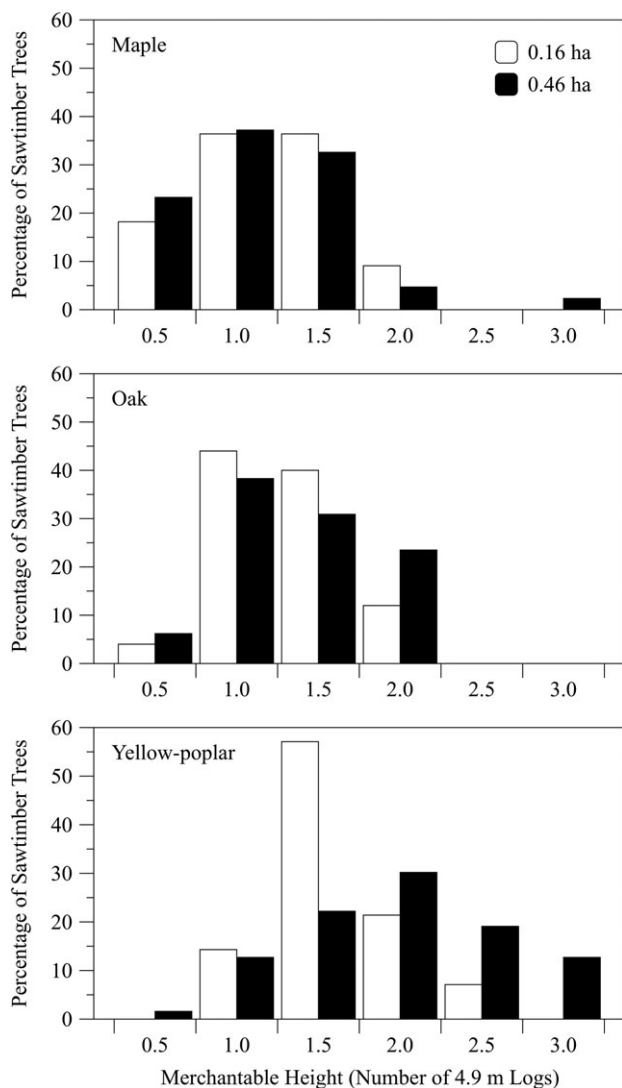


Figure 2 Merchantable height distribution for sawtimber-sized trees (dbh ≥ 30.5 cm) by species group as measured through the number of 4.9 m (16 ft) logs per tree.

light) increase with larger gap size or in locales within gaps known for higher light availability (i.e. centres and northern portions of gaps) the dominance of shade-intolerant species will become greater. A review included in Kern *et al.* (2013) suggested empirical studies of temperate forests in the Northern Hemisphere have shown mixed support for the gap partitioning hypothesis. Some work has shown species partitioning among gap sizes and/or spatially within gaps (Smith, 1981; Gray and Spies, 1996; Holladay *et al.*, 2006; Huth and Wagner, 2006; Mountford *et al.*, 2006; Powers *et al.*, 2008; Van Couwenberghe *et al.*, 2010; Arseneault *et al.*, 2011; Vilhar *et al.*, 2015), while other work has found little evidence of this (Sipe and Bazzaz, 1995; Coates, 2002; Raymond *et al.*, 2006).

Long-term tree recruitment trends among the three primary species groups in this study were strongly linked to the apparent growth environment created by differing gap size. In support of the gap partitioning hypothesis, species recruitment showed a

distinct relationship with species shade tolerance and gap size. The smallest gap size was dominated by red and sugar maple, two species known for their high degree of shade tolerance (Godman *et al.*, 1990; Walters and Yawney, 1990). Work within the region has consistently shown that this species group can dominate upland stands following the creation of small canopy openings associated with single-tree selection systems (Della-Bianca and Beck, 1985; Schuler, 2004; Neuendorff *et al.*, 2007; Keyser and Loftis, 2013) or tree mortality (Abrams, 1998; Tift and Fajvan, 1999; Cole and Lorimer, 2005). At the other end of the shade tolerance spectrum, recruitment by the shade-intolerant yellow-poplar (Beck and Della-Bianca, 1981) increased with increasing gap size following trends found for this species in the region (Smith, 1981; Dale *et al.*, 1995; Jenkins and Parker, 1998; Morrissey *et al.*, 2010). Furthering support for the gap partitioning hypothesis, the oak group composed of species of intermediate shade tolerance that can reach maximum juvenile height growth rates in light levels below 25% full sun (Phares, 1971; Gottschalk, 1994; Rebbeck *et al.*, 2012) had the highest relative density in the intermediate gap size.

Stand and individual tree growth trends 51 years following gap creation had a distinct linkage to gap size and the species assemblage was consistent with the environmental parameters, particularly light, that would be expected initially in these gaps (Fischer, 1981). Total per ha sawtimber volume provided an overall indicator of the impact gap size had on forest development. Increased volume with increasing gap size was also observed by Dale *et al.* (1995) who completed a 30-year evaluation of numerous gap size studies across the region including a subset of the Robinson Forest plots used in our work. Dale *et al.* (1995) found a positive relationship between gap size and 30-year merchantable volume growth for gaps up to 0.40 ha with larger gaps having a nominal effect on volume growth. A related study from the southern Appalachian region by Shure *et al.* (2006) found that 17-year total tree biomass increased across a gap size range of 0.016 ha to 0.40 ha.

The lack of merchantable (sawtimber) volume in the 0.02 ha gap was in clear contrast to the larger openings. While the 0.02 ha gaps facilitated initial regeneration of maple (1400 trees ha^{-1}), oak (2800 trees ha^{-1}) and yellow-poplar (604 trees ha^{-1}) groups following two growing seasons (Lhotka, 2013), it is likely that the majority of the 0.02 ha gap areas were under the influence of the adjacent tree canopy during a considerable portion of the study period. Impacts of adjacent tree canopies on forest development within the 0.02 ha gaps would likely have increased through time due to lateral crown growth into the openings especially given that these effects have been shown to be most pronounced in small gaps (Hibbs, 1982; Cole and Lorimer, 2005). Edge effects within the 0.02 ha gaps may have had a direct impact on long-term species retention and overall volume growth. Dale *et al.* (1995) reached a similar conclusion at year 30 in their evaluation of a larger suite of study locations where they observed that edge effects resulted in lower tree densities and reduced tree height and diameter. Related research in other forest types has documented the reduction of available light in a zone associated with a gap's edge and that these environments can have appreciable negative impacts on tree growth and forest development at the outer margins of a gap (York *et al.*, 2003; Voicu and Comeau, 2006; Powers *et al.*, 2008). Other authors have noted that tree growth and recruitment can vary by within

gap location for larger openings, but does not differ by location in small gaps due to more uniform reduced light conditions resulting from edge effects (Coates, 2002). Shure *et al.* (2006) found similar patterns for total tree biomass with small gaps resulting in uniform reductions in biomass across the entire gap.

From an individual tree perspective, mean tree volume patterns between oak and yellow-poplar groups in the 0.16 ha and 0.46 ha gaps may also indicate potential effects by forest edge and gap partitioning. One would expect that with increased gap size and a probable increase in available light (Fischer, 1981; Takenaka, 1988; Chen *et al.*, 1993) that growth and volume accumulation at the tree level may increase. While this pattern was present for oak, the mean dbh and per tree volume of yellow-poplar did not differ between the 0.16 ha and 0.46 ha gaps. Dale *et al.* (1995) found large reductions in the density, basal area and total volume near gap edges when compared to the centre portion of the gap and such reductions were most pronounced for shade-intolerant species. These findings by Dale *et al.* (1995) provide a potential explanation as to why yellow-poplar did not differ in size between the 0.16 ha and 0.46 ha gaps. It is probable that its recruitment in the intermediate sized gap was more limited to a gap's centre where light would have been higher and more similar to the increased light likely present across much of the larger 0.46 ha gaps.

Conclusions and implications

A stark contrast was present among the species composition and growth trends in the 0.02 ha gaps vs the two larger sizes. Reductions in maple were balanced by an increase in the mid-tolerant oaks and intolerant yellow-poplar in these larger openings. While the relative density of oak was highest in the 0.16 ha gaps, oak had significantly higher mean per tree volume in the largest gap size. Whereas the per tree volume of yellow-poplar did not differ among the two larger gap treatments, yellow-poplar accounted for a significantly higher relative density of sawtimber-sized trees in the 0.46 ha gaps. Increased sawtimber volume ($\text{m}^3 \text{ha}^{-1}$) in the 0.46 ha opening is therefore likely a function of the combined effect of increased oak per tree volume growth along with the increased proportion of the fast-growing, shade-intolerant yellow-poplar.

These findings underscore the complexity of gap development where shifting gap sizes not only can affect the growth rate of a given species but it can also alter the recruitment of species groups which may fundamentally alter long-term stand growth trends. While work presented here represents observations from one forest type and a single location, it does further the understanding of how species compositional shifts and tree size responses resulting from changing gap sizes can alter important stand growth parameters, such as sawtimber volume, that have fundamental effects on the management and forest utility in gap-based silviculture.

From a management perspective for the Central Hardwood Forest Region where the study was conducted, species and growth patterns provide important long-term data that can be used to help guide the selection of opening sizes within the development of gap-based silvicultural approaches. The smallest gap size tested (0.02 ha) did not promote the recruitment of oak which is the most desired species group in the region

from the perspective of forest products markets and the contribution to non-market values such as wildlife habitat (McShea and Healy, 2003; Dey, 2014; Keyser *et al.*, 2016). The forest environment created by the 0.02 ha gaps also appeared to slow forest development through reduced growth and all indications from mid-rotation data suggest that the future sawtimber yield potential in these gaps will be poor.

While our data suggest that the use of the 0.02 ha gap size in the Central Hardwood Forest Region may not be prudent, the benefits of 0.16 ha vs 0.46 ha gaps may be dependent on management objectives. From the perspective of increasing oak recruitment, the 0.16 ha gap resulted in the highest relative density of oak and sawtimber-sized oak trees. However, the largest opening size had a distinct advantage in sawtimber yields linked to increased recruitment of yellow-poplar and per tree volume of the oak group. In the context of promoting enhanced structural heterogeneity and species diversity, multiple gap sizes could be applied within a stand thereby leveraging the varied microclimates and forest development patterns that would result. Another consideration relating to the application of gaps is how they may be manipulated or created in subsequent stand entries. While this study only evaluated initial isolated gaps, application of gap-based silviculture could utilize the future expansion of existing gaps, formation of new isolated gaps, or the creation of overlapping gaps.

One factor that could influence the relationships between gap size and species proportions and yield outcomes observed in this study is the application of intermediate silvicultural treatments. Perhaps thinning or release could have been used to increase growth rates in the 0.16 ha opening and/or oak recruitment and retention in the 0.46 ha opening. Each of these potential outcomes could influence the selection of a prudent opening size. For example, if management wanted to ensure oak maintenance without intermediate treatments, selection of a 0.16 ha gap would be appropriate whereas 0.46 ha gaps might be appropriate if treatments like crop tree release could be used to maintain and favour oak in the larger gaps. Therefore, future research on the combined effect of initial gap size and application of intermediate treatments may be warranted to inform the development of gap-based silvicultural systems for the Central Hardwood Forest Region.

Gaps in this study were created through chainsaw felling of merchantable trees, girdling of non-merchantable sawtimber-sized trees, and frill and herbicide application to trees between 7.6 cm and 30.5 cm dbh. This manner of gap formation may have resulted in a lag over at least the first growing season where residual canopy coverage would have been present while treated tree succumbed to the effects of girdling and herbicide application. Observations during the 2011 inventory also suggest a few of the girdled trees likely survived through the study duration. The authors were unable to determine the exact effects these factors may have had on growth and recruitment trends among species groups and gap treatments. However, given the physiologic characteristics of the three species groups evaluated, a delay in the maximum available light increase associated with a gap size could have favoured mid-tolerant oaks and shade tolerant maples at least initially in gap development. This potential influence raises an interesting thought on future research relating to the roles canopy tree retention or staged tree removal in gaps may play in promoting species groups like oak through gap-based silvicultural systems in the region.

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Conflict of interest statement

None declared.

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