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Research Article

Silviculture

Composition and Structure of Reproduction in Group Selection Openings after 20 Years in a Southern Appalachian Mixed-Hardwood Forest

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Abstract

Following harvests by even-aged methods in mixed-hardwood forests, desirable oak (*Quercus* spp. L.) reproduction can be quickly overtopped by shade-intolerant pioneer species. In a long-term, operational-scale study of uneven-aged management by group selection, we inventoried 10- and 20-year-old reproduction following two harvest entries in a mature, dry-mesic southern Appalachian upland hardwood stand. Our study objectives included evaluating the species composition and structure of reproduction in relation to opening size (0.05 ha to 0.41 ha), position in openings (center or edge), uneven-aged diameter structure, and evidence supporting the delayed oak dominance hypothesis. Opening size had no effect on reproduction from either entry. After 10 years (but not 20) yellow-poplar (*Liriodendron tulipifera* L.) stem density and basal area were greater in opening centers; oaks were greater at edges. Position did not affect red maple (*Acer rubrum* L.) or other tolerant species. Diversity significantly increased between 10 and 20 years, suggesting evidence supporting the delayed oak dominance hypothesis. Early results from this study suggest that small openings can be used to regenerate desirable midtolerant and intolerant species in Appalachian mixed-hardwood stands on intermediate quality sites where uneven-aged stand structure is important for timber management and other goals such as visual appearance and early successional habitat.

Study Implications: Periodic harvests of small groups (0.05 to 0.41 ha) of mature trees in dry-mesic Appalachian oak-dominated, mixed-hardwood stands, followed by site preparation and competition release treatments to control undesirable shade tolerant species, can result in openings stocked with desirable shade midtolerant and intolerant reproduction after 20 years. Centers of openings will be dominated by yellow-poplar, but oak reproduction can be most prevalent around the periphery. Group selection is a flexible method of uneven-aged management that can be used to meet regeneration objectives and related goals such as early successional habitat and visual quality.

Keywords: dominance hypothesis, group selection, opening size, *Quercus*, self-thinning

Gap-based partial cutting practices have been proposed as an appropriate silvicultural system to address multiple management objectives of visual quality, habitat, regeneration, resiliency, biodiversity, and sustainability of ecosystems in many forest types in North America (Coates and Burton 1997), which includes the Central Hardwood Region (CHR) of the eastern United States. There, oaks are both characteristic and keystone canopy species with high economic and habitat value in the mixed-hardwood forests (Fralish 2004). However, recruitment and development of midtolerant oak reproduction following harvests has decreased in the CHR likely because of altered historical disturbance regimes during the 1900s (such as suppression of wildland fire) that have favored tolerant species (Abrams 2003, Nowacki and Abrams 2008) and stand regeneration by clearcutting that favors fast-growing intolerant species, such as sweetgum (*Liquidambar styraciflua* L.) (Johnsen and Krinard 1988) or yellow-poplar (Brashears et al. 2004). The regeneration ecology of oaks is well known (Johnson et al. 2002); advance oak reproduction must develop a large root system before meaningful height growth is initiated and maintained (Sander 1971). The multilayered forests of the southern Appalachians section of the CHR consist of nearly 100 predominantly cold-deciduous hardwood species that can be classified in two groups: desirable, which are large, shade intolerant canopy species that are well formed and can have high commercial and/or wildlife habitat value, or undesirable, which are typically small, shade tolerant species that are poorly formed and/or have little commercial value, but may provide soft mast for wildlife (Della-Bianca and Beck 1985). Depending on available light resources admitted through canopy openings to the forest floor, advanced reproduction of desirable oaks cycles through alternating phases of growth, top-dieback, and basal resprouting (Runkle and Yetter 1987). The combination of small canopy openings resulting from death of single trees, combined with the middle canopy of shade tolerant species, hinders development and growth of desired advance reproduction of intolerant species into the canopy on dry-mesic sites (Della-Bianca and Beck 1985).

It has long been known that small canopy openings resulting from single-tree selection favors regeneration by shade tolerant species in the southern Appalachians (Frothingham 1931, Della-Bianca and Beck 1985). Frothingham (1931),

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however, first suggested that larger openings resulting from group selection harvests could favor intolerant species. Group selection has been studied extensively in central and northern parts of the CHR and elsewhere to investigate effects of gap size, orientation, substrate, and age on composition and structure on reproduction of oaks and other desired species (Zhu et al. 2014, Kern et al. 2017). Studies of group selection have not been conducted in the southern Appalachians, however, which has environmental conditions and species composition different than elsewhere in the CHR (Cook et al. 1998).

Group selection research has shown that small openings (<0.05 ha) promote shade tolerant species and large openings (>0.40 ha) favor intolerant species; oak reproduction, which is semitolerant of shade as juveniles, occurs most frequently in intermediate-sized openings (Lhotka 2013). In intermediate and large openings, rapidly growing pioneer species present the primary source of competition to slowly growing advance oak reproduction following harvests in much of the CHR (Jenkins and Parker 1998, Lhotka 2013). Oliver (1978) observed that second- and third-decade self-thinning in pioneer-dominated stands can allow emergence of slower growing, intermediate oaks as codominants, and proposed the delayed oak dominance hypothesis. The hypothesis has been specifically tested by Steiner et al. (2018) and observed from inventory data in bottomland (Johnsen and Krinard 1988) and upland stands (Hilt 1985), but little studied elsewhere.

The purpose of this article is to summarize 10- and 20-year responses of reproduction resulting from two entries in a 1988 study of group selection harvests in a southern Appalachian mixed-hardwood forest. Objectives of this study were strongly influenced by results from a long-term study of single-tree selection in an adjacent stand showing lack of desirable reproduction of mid and intolerant species (Della-Bianca and Beck 1985) and favorable results from a group selection study in northern hardwoods (Leak and Filip 1977). Initial objectives of this study were associated primarily with questions regarding uneven-aged management, particularly in relation to arguments by Roach (1974) concerning application and sustainability of the group selection method in hardwood forests: (1) Will group selection result in a balanced (i.e., reverse J-shaped curve) stand structure? (2) What size opening is needed for regenerating intolerant species, particularly oaks? Two additional study objectives were included during the second harvest entry: (3) Does position in openings affect composition and structure of reproduction? (4) Is evidence available in support of the delayed oak dominance hypothesis?

Methods

Site and Vegetation Description

The Frothingham group selection study was installed in the Boyd Branch watershed of the Bent Creek Experimental Forest, a special use area in the Pisgah Ranger District of the Pisgah National Forest, in western North Carolina (35.489°N, –82.645°W) (Figure 1). The subtropical/continental climate consists of short, mild winters (mean January temperature: –14.0°C) and warm, humid summers (mean July temperature: 22.3°C). Precipitation averages 1,220 mm annually and is distributed uniformly among seasons; snowfall averages 280 mm annually. The 29.9 ha study area occupies a low-elevation (720–850 m) shallow, east-facing cove with soil moisture regimes ranging from submesic to subxeric. Soils

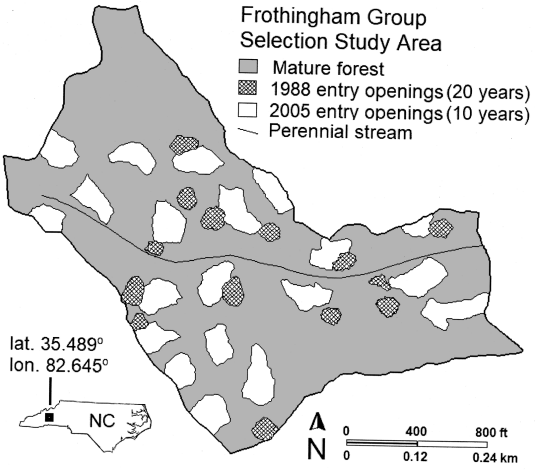

Figure 1. The Frothingham group selection study area showing openings for the first entry (1988) and the second entry (2005). (Map created by H. McNab using MicroSoft Paint software.)

are deep (>100 cm), predominantly Ultisols (Evard, Cowee, Toecane series) in residuum on gentle slopes and Inceptisols (Tusquitee series) in colluvium on steep slopes and in narrow bands adjacent to perennial streams. The study area is part of a larger tract previously used for subsistence farming by the Boyd family during the mid to late 1800s (Nesbitt 1941). Although none of the study area had been cultivated, it was likely an open-canopy woodlot with an herbaceous layer of native grasses and tree and shrub basal sprouts, which was burned periodically to promote browse for grazing by livestock. Except for the regional demise of American chestnut (*Castanea dentata* [Marsh.] Borkh.) in the 1920s, resulting from a blight fungus (*Cryphonectria parasitica* [Murrill] M.E. Barr.), there are no records of other human-related disturbances, such as commercial timber harvests. Predominant vegetation on middle and lower slopes consists of a high canopy (30 m) of merchantable mixed hardwoods primarily of midtolerant to intolerant oaks (black [*Q. velutina* Lam.], chestnut [*Q. montana* L.], scarlet [*Q. coccinea* Muenchh.], white [*Q. alba* L.], and northern red [*Q. rubra* L.]) and hickories (mockernut [*Carya tomentosa* Sarg.] and pignut [*C. glabra* Miller]); intolerant yellow-poplar occurs primarily on mesic soils along streams and also as scattered individuals throughout. Middle and lower canopies are dominated by small, shade tolerant, generally unmerchantable mixed hardwoods including red maple, sourwood (*Oxydendrum arboretum* L.), flowering dogwood (*Cornus florida* L.), blackgum (*Nyssa sylvatica* Marsh.), and witch hazel (*Hamamelis virginiana* L.). Common tall (>2 m) evergreen shrubs include rosebay rhododendron (*Rhododendron maximum* L.) on moist sites and mountain laurel (*Kalmia latifolia* L.) on dry sites.

Preharvest Stand Sampling

In winter 1988, advance reproduction (height < 1.37 m) and small trees (diameter breast height (dbh) ≥ 1 cm to 15.2 cm) were inventoried by species and diameter on 0.004 ha sample plots systematically distributed throughout the stand at the rate of 2.5 plots per ha. All large trees (>15.2 cm dbh) were inventoried individually by species and dbh in a total cruise of the study area. Tree diameters ranged to a maximum of 89 cm and approximated the balanced distribution

Table 1. Species subgroup, species group (Spec. Group), shade tolerance class (Tol. Class), reproduction density (Repro. Density, height <1.37 m), tree stem density (≥1 cm diameter breast height), basal area (BA), quadratic mean diameter breast height (dbhq), and importance value (IV, relative stem density + relative basal area) by species subgroups and overall subgroups of the mature, mixed-hardwood stand occupying the study area before the first harvest entry in 1988.

Species Subgroup	Spec. Group	Tol. Class	Repro. Density	Tree Density (n/ha)			BA m^2/ha	dbhq (cm)	IV 200
Tree Species				1–10 cm	>10 cm	Sum			
Red oak									
Quercus spp.*	D	M	2,406	6.5	29.1	35.6	2.50	29.9	10.3
Northern red oak	D	M	8,190	6.5	3.9	10.4	0.38	21.7	1.8
Overall species	D	-	10,596	13.0	33.0	46.0	2.88	28.2	12.2
White oak									
Chestnut oak	D	M	2,566	26.0	58.8	84.8	5.54	28.8	23.2
White oak	D	M	5,898	6.5	21.1	27.6	2.21	32.0	9.0
Overall species	D	-	8,464	32.5	79.9	112.4	7.75	29.6	32.2
Yellow-poplar									
Yellow-poplar	D	I	2,097	26.0	133.8	159.8	9.00	26.8	38.9
Other desirable									
Sweet birch	D	I	291	110.5	21.1	131.6	0.76	8.5	9.3
Black locust	D	I	944	13.0	18.6	31.6	0.65	16.2	3.8
Hickory spp.*	D	M	504	32.5	5.4	37.9	0.27	9.5	2.9
Miscel. species (1)*	D	I	17	6.5	1.5	8.0	0.10	12.4	0.7
Overall species	D	-	1,756	162.5	46.6	209.1	1.78	10.4	16.8
Red maple									
Red maple	U	T	65,924	273.0	88.0	361.0	3.48	11.1	30.4
Other undesirable									
Miscel. species (2)*	U	T	6,355	728.0	95.2	823.2	4.19	8.1	56.5
Witch hazel	U	T	944	169.0	0	169.0	0.16	3.5	9.2
Miscel. species (3)*	U	T	3	32.5	0	32.5	0.04	4.1	1.8
Blackgum	U	T	422	19.5	2.4	21.9	0.06	5.7	1.3
Serviceberry	U	T	553	13.0	0	13.0	0.01	1.5	0.7
Overall species	U	-	8,277	962.0	97.6	1059.6	4.45	7.3	69.6
Overall groups	-	-	97,115	1469.0	478.9	1947.9	29.34	13.8	200.0

Species group: D, desirable; U, undesirable. Tol. class, shade tolerance class: I, intolerant; M, midtolerant; T, tolerant. **Quercus* spp.: scarlet oak (*Q. coccinea*) and black oak (*Q. velutina*).
*Hickory spp.: mockernut (*Carya tomentosa*) and pignut (*C. glabra*).
*Miscellaneous species (1): white ash (*Fraxinus americana*), black cherry (*Prunus serotina*), and shortleaf pine (*Pinus echinata*) combined. Miscellaneous species (2): flowering dogwood (*Cornus florida*), sourwood (*Oxydendrum arboreum*), and sassafras (*Sassafras albidum*). Miscellaneous species (3): American beech (*Fagus grandifolia*) and American holly (*Ilex opaca*).
Other undesirable: witch hazel (*Hamamelis virginiana*), blackgum (*Nyssa sylvatica*), and serviceberry (*Amelanchier arborea*).

of an uneven-aged stand, although mixed-species stands of eastern hardwoods are typically even-aged because of their stratified structure associated with shade tolerance (Oliver 1980). The prestudy inventory of advance reproduction and trees in the study area revealed a mean total basal area of 29.3 m^2/ha distributed among 20 species (Table 1). Five species of oaks (listed below) and yellow-poplar characterized the overstory. The small component of shortleaf pine (*Pinus echinata* Mill.), a conifer intolerant of shade and requiring exposed soil for best seed germination, is evidence of past land use for subsistence agriculture before this tract was acquired for inclusion in the national forest, around 1920. This species composition of mixed-hardwoods and scattered conifers corresponds well with the extensively occurring Southern Appalachian Oak Forest terrestrial ecosystem CES202.886, which occurs on mountainous landscapes from central Virginia to south-western North Carolina (NatureServe 2020). In 1988, mean age of dominant and codominant red oaks was 51 years (n = 8, range 33–86 years) and 69 years (n = 27, range 21–155 years) for white oaks. Oak site index averages approximately 24 m (range 22–27 m, 50-year base). Culmination of mean annual volume growth of dry-mesic hardwood stands averages 3.04 m^3/ha/year at approximately 90 years (USDA Forest Service 1994). Except for a narrow band of mixed mesophytic hardwoods along a perennial stream and on xeric sites along a ridge crest, the study area was relatively uniform in species composition and structure of vegetation was treated as a single stand.

Timber Harvests and Herbicide Site Preparation

The Frothingham study was established in 1988 to investigate group selection as a corollary to an adjacent long-term study of single tree selection (Della-Bianca and Beck 1985). Briefly, the study design specified management by area control with openings ranging in size from 0.10 ha to 0.40 ha. Openings were widely distributed on sites with acceptable regeneration potential, damaged canopy trees or poor stocking of mature trees; rotation length is 60 to 80 years and entry cycle is 10 to 15 years. Two entries have been made, in 1988 and 2005, when 14 and 24 openings were harvested, respectively. The 14 openings harvested in 1988 averaged 0.10 ha (range 0.05–0.14 ha); size of the 24 openings harvested in the 2005 entry averaged 0.29 ha and ranged from 0.13 ha to 0.41 ha. For both entries, all merchantable pulp wood and saw timber was cut using chainsaws and skidded to landings using either a farm tractor (1988 entry) or forestry-type wheeled skidder (2005).

Site preparation consisted of herbicide and hand tools treatment using cut stump and basal spray applications. Cut stumps were sprayed with a 50:50 ratio of triclopyr amine and water. Streamline basal spray was made with triclopyr ester mixed with mineral oil and bark penetrant additive at a 20% mixture. All residual trees between 2.54 and 20 cm dbh were cut. The cut surface of stumps of red maple, sourwood, blackgum, yellow-poplar, mountain laurel, rhododendron, vines (primarily oriental bittersweet [*Celastrus orbiculatus* Thunb.]), and exotic invasive species were sprayed with herbicide. Herbicide treatment of cut stumps was a standard method of site preparation used by national forests and necessary to control aggressive basal sprouting of tolerant species, which can quickly occupy a large proportion of growing space after harvests (Smith 1981, Fei and Steiner 2009). Within three growing seasons after harvest selected desirable species (primarily oaks) were released from competition using streamline basal spray application of 20% triclopyr ester herbicide mixed with mineral oil and an added compound consisting of wetting agent, sticker, and bark penetrant. Release treatments targeted sprout clumps of the species specified for site preparation. Site preparation and release treatments were applied by a contractor; field data were not collected on stems treated in the harvested openings.

Sample Plot Design and Data

Reproduction was inventoried once for each of the two entries: at 10 years after the 2005 entry and 20 years after the 1988 entry. Two sample plots (circular 0.004 ha, 3.6 m radius) were established at two locations (hereafter positions) in each opening: the center and edge. In a random direction from the center, each edge sample plot was placed so its boundary coincided with the boundary of the harvested opening. Edge plots were excluded and reselected that were adjacent to a logging road or that varied markedly in site conditions from the center plot, such as landform differences. Edge sample plots in the 2005 openings were not excluded if they were adjacent to an opening harvested in the 1988 entry. All tree reproduction ≥0.5 cm dbh was inventoried by species and 2.5 cm dbh classes in openings of each entry. Total height and dbh of several yellow-poplar trees in the center and edge sample plots of each opening were measured for development of a model for predicting total height of individual trees from inventory data. We selected yellow-poplar for height modeling because it is the predominant pioneer species on mesic and dry-mesic sites in the southern Appalachians and as such is the primary competitor of oaks and intolerant species (Beck and Hooper 1986). Yellow-poplar grows rapidly in height soon after seed germination and provides a measure of size that oaks must attain to be a component of the newly developing stand (Beck and Della-Bianca 1981).

Age of the 1988 preharvest stand was estimated from ring counts on stumps from trees cut in the third entry, in fall 2017. Oak stumps of various sizes were randomly selected in 12 openings and measured for diameter outside bark from the pith across the maximum and minimum stump surface dimensions. Stumps were identified by species and annual growth rings were counted in the field using a 10-power hand-held magnifier.

Species Groupings for Analysis

Tree species were classified in two primary groups (desirable or undesirable) associated with their traditional economic value (Della-Bianca and Beck 1985) and six secondary subgroups according to their habitat values (such as oaks) or focus of research interest (such as red maple, Abrams 1998) (Table 1). Desirable species are intolerant to midtolerant of shade, attain large size, form the overstory canopy and have commercial timber value; some (oak and hickory) are also important for wildlife because of their hard mast (acorn or nut) production. Undesirable species are shade tolerant, small, form the canopy midstory and have low commercial value, although many species produce soft mast used by wildlife. The desirable species group was further separated into four subgroups: red oak (subgenus *Erythrobalanus*), white oak (subgenus *Leucobalanus*), yellow-poplar, and other-desirable. The red oak subgroup included three species (ranked by affinity with decreasing soil moisture): scarlet < black < northern red; the white oak subgroup included two species (chestnut < white). The five oak species were separated into

two subgroups because of their relative differences in shade tolerance as juveniles: red oak < white oak (Johnsen et al. 2002). Yellow-poplar was evaluated as a desirable subgroup because of its high commercial value and silvical characteristics as an aggressive, long-lived, mesophytic, intolerant species with wind-dispersed seeds that germinate best on mineral soil following disturbance of the forest floor. It is typically a pioneer species on heavily disturbed mesic sites where its high stem density and rapid growth can result in dense stands that retard growth of other species, but it can also persist as scattered individuals that become established in old-growth stands (Beck and Della-Bianca 1981). The other-desirable subgroup (hereafter desirable) includes minor species, primarily white ash (*Fraxinus Americana* L.), sweet birch (*Betula lenta* L.), black locust (*Robinia pseudoacacia* L.), mockernut hickory, and pignut hickory.

The undesirable species group was separated into two subgroups: red maple and other undesirable. Red maple, a light-seeded species, was evaluated separately because of its unusual ecological attributes of high shade tolerance and relatively quick growth response to increased light, thereby allowing it to capture growing space in openings following stand disturbances and persist as a long-lived species as it ascends in the canopy (Abrams 1998). In addition, red maple occurs across a range of site qualities and following harvests can present strong competition to desirable reproduction as rapidly growing basal sprouts from stumps during early stand development (Steiner et al. 2018). The other-undesirable subgroup (hereafter undesirable) includes shade tolerant species: flowering dogwood, sourwood, blackgum, witch hazel, serviceberry (*Amelanchier arborea* [F.Michx.] Fernald), American beech (*Fagus grandifolia* Ehrh.), and American holly (*Ilex opaca* Aiton.) in the midstory that are small and poorly formed and have greater value as producers of soft mast for wildlife habitat than for timber products. In review, tree composition was classified first in two groups, desirable or undesirable, and then in six subgroups for data summary and analysis: red oak, white oak, yellow-poplar, desirable, red maple, or undesirable.

Statistical Analysis

There were no imposed experimental treatments in our study. Species composition and structure of tree reproduction were examined to evaluate their response to opening size and position in openings. For the first entry (1988), openings were intentionally small (mean 0.10 ha, range 0.05–0.14 ha) to investigate minimum size required for establishment of intolerant desirable species. For the second entry (2005) openings were larger (mean 0.29 ha, range 0.12–0.41 ha) to follow operational national forest guidelines for uneven-aged management using the group selection method (USDA Forest Service 1994). Reproduction following the 1988 entry was inventoried in 13 of the 14 harvested openings; one opening was destroyed by a logging skid road constructed for the 2005 entry. Twenty-three openings were harvested in the 2005 entry, of which 14 were sampled.

Regression was used to evaluate the distribution of tree stems per hectare by 5 cm dbh classes of the preharvest stand and combined reproduction resulting from the two harvest entries for evidence of a reverse "J-shaped" (negative exponential) curve that is characteristic of uneven-aged stands (Leak and Filip 1977). Diameter distribution diminution quotients (Q) were calculated using the regression method of Leak (1963). The response of reproduction to opening size and position in openings was quantified by stem density (hereafter density), basal area and quadratic mean dbh (dbhq) of species subgroups for each entry. Quadratic mean dbh was calculated from plot stem density and basal area (Curtis and Marshall 2000). Density and basal area of subgroups were standardized as relative percent values of sample plot totals by center and edge positions and overall (pooled center and edge positions) opening. Histograms of plot mean stem densities indicated a tendency toward positive skewed distributions. The arcsine-square root transformation was used to approximate normal distributions (McDonald 2014). Untransformed means and standard deviations (sd) are presented in tables. A relationship between tree age and stump diameter outside bark was examined by oak subgroup using correlation and regression analysis. Correlation and linear regression were also used to examine relationships and test for effects of opening size on response variables of density, basal area and dbhq by species subgroup for pooled and nonpooled opening position (center, edge) by reproduction cohort age. Regression analysis was used to evaluate effects of opening size alone (disregarding center and edge sample positions) and in combination with position on mean total height of yellow-poplar at each reproduction cohort age. One-way analysis of variance (ANOVA) was used to test for significant differences of opening sample position on density, basal area and dbhq by species subgroup of reproduction resulting from each entry. Statistical differences of density, basal area and dbhq response variables among the six subgroups of species were not informative for objectives of our study and were not evaluated. The delayed oak dominance hypothesis was examined by one-way ANOVA of individual species subgroup changes of stem density between the two harvest entries and community structure change of combined subgroups using a modification of the method presented by Solow (1993) based on Simpson's index of diversity. Version 3.5.1 of R was used for data analysis (R Development Core Team 2011). Significance was determined at the $p = .05$ level.

Results

Before the first entry, stem density of advance reproduction (height <1.37 m) on sample plots in the mature stand throughout the entire study area consisted primarily of the red maple subgroup (69%), red oak (11%), and white oak (9%); yellow-poplar was 2% (Table 1). The midstory (height ≥1.37 m and dbh <10 cm) consisted primarily of shade tolerant red maple and flowering dogwood in the undesirable species groups. The overstory was dominated by species in the two oak subgroups followed by yellow-poplar. The diameter distribution of the entire pretreatment stand displayed a reverse J-shaped curve approximated by a calculated Q of 1.24 (Figure 2A). Mean age of the two oak subgroups in 1988 was 66 years (n = 34, sd = 29 years, range = 21–155 years). For the white oak subgroup, tree age was correlated with stump diameter outside bark (dob) (n = 27, $r = 0.669$, $p \leq .001$), expressed by the relationship

$$\text{Age (years)} = -8.35 + 1.26\,(\text{stump dob in cm}) \quad (1)$$

with a standard error of estimate of 23.08 years. An age to stump dob relationship for the red oak subgroup could not be evaluated because the sample size was too small (n = 7).

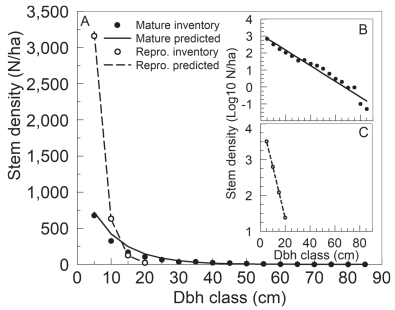

Figure 2. Size class (diameter at breast height [dbh]) distributions of tree stem densities by age cohort in the study area. (A) Inventoried and predicted stem densities for mature trees preharvest and reproduction postharvest.* (B) Log10-transformed preharvest mature stand. (C) Log10-transformed reproduction in the combined 1988 (20 years old) and 2005 (10 years old) openings. *Reproduction combines 1988 and 2005 harvest openings.

Opening Size and Position in Opening

Opening size was not significantly correlated with overall (pooled center and edge positions) mean relative density or basal area for any species subgroup in either of the two age classes of reproduction (not shown). Pearson correlation coefficients were relatively low for basal area of the 10-year-old red oak ($r = -0.20$) and white oak reproduction ($r = -0.25$) and were still lower for the 20-year-old reproduction: $r = -0.07$ for red oaks and $r = -0.01$ for white oaks. Correlation analysis of the effects of opening size based on nonpooled positions, however, indicated a significant relationship ($r = 0.61$, $p < .05$) of mean relative density for 10-year-old reproduction of the red oak subgroup in opening centers (not shown). Pearson's r was not significant for similar correlations between opening size with mean relative density and basal area by position and reproduction age class for the other species subgroups.

Position in openings alone (without the influence of opening size) significantly affected relative stem density and relative basal area of 10-year-old reproduction for the red and white oak subgroups and yellow-poplar (Table 2). Relative basal area was greater for the red oak ($p < .05$) and white oak ($p < .05$) subgroups at the edges of openings than in centers (Figure 3). In a reverse relationship, yellow-poplar basal areas were greater ($p < .05$) in centers compared with edges. Mean relative basal area between the center and edge positions were not significant different for the desirable, red maple and undesirable subgroups. In the 20-year-old openings the only significant effect of position on species was for mean basal area of red maple, which was greater ($p < .05$) at the edge than at the center of openings (Table 2). In openings of both harvest entries, basal area and dbhq of overall species subgroups were significantly ($p < .01$) greater in center compared with edge positions.

Mean height of yellow-poplar reproduction was not correlated with opening size across pooled sample positions for either the 10-year-old reproduction ($\bar{x} = 2.35$ m, n = 28, $r = 0.59$, $p = .058$) or at 20 years ($\bar{x} = 6.67$ m, n = 24, $r = 0.12$, $p = .713$) (not shown). Analysis of variance, however, indicated position in openings had a significant effect ($p < .01$) on mean height of 10-year-old yellow-poplar reproduction (Figure 4). Mean total height was 3.1 m (n = 16, sd = 1.39 m) in the center of openings and 1.3 m (n = 12, sd = 1.20) at the edge, a difference of 1.8 m. For the 20-year-old openings of the 1988 entry, mean total height of yellow-poplar was 7.7 m (n = 12, sd = 3.29 m) in center compared with 5.7 m (n = 12, sd = 3.22 m) at edge positions, but the difference of 2 m was not significant ($p = .14$).

A quadratic multiple regression model was developed to evaluate the combined effects of opening size, position in opening and their interaction on mean total height of yellow-poplar at each cohort age. For the 10-year-old yellow-poplar subgroup the best model (n = 28, $R^2 = 0.51$, $p = .0001$) included opening size ($p = .005$) and a categorical variable for position ($p = .0002$); the interaction was not significant ($p = .54$):

$$\text{Height (m)} = 1.7745 + 14.2866\,(\text{size}^2) - 1.8896\,(\text{edge position}) \quad (2)$$

where size is opening area in hectares squared and edge position is 1 or 0 (for edge or nonedge position). Variation explained by position increased the level of significance of opening size from $p = .058$ to $p < .001$ for the 10-year-old trees. Model (2) predicts mean yellow-poplar height at 10 years increases from 1.9 m to 3.9 m in opening centers as opening size increases from 0.13 ha to 0.41 ha (Figure 5). The position coefficient indicates yellow-poplar height averaged 1.9 m shorter at edges compared with centers of openings. A similarly formulated model for height of the 20-year-old yellow-poplar saplings in the small 1988 openings was not significant (n = 24, $R^2 = 0.10$, $p = .32$) and is not shown.

Species Composition and Structure

Mean total basal area of reproduction in the openings at 10 years was 8.0 m^2/ha and 14.1 m^2/ha at 20 years, an increase of 77%. (Table 2). Basal area of all species subgroups increased between 10 and 20 years, but none of the changes were significantly different. The overall percent increase of basal area between 10 and 20 years was less in opening centers (71%) compared with edges (92%).

Between the first and second entries, the overall mean basal area of yellow-poplar decreased from 67% to 47% ($p = .17$), and the desirable subgroup from 15% to 12% ($p = .73$) (Figure 6). This total decrease of 23% was matched by a total increase of 11% for the red and white oak subgroups ($p = .57$ and $p = .70$, respectively) and 12% for the combined red maple ($p = .49$) and undesirable subgroups ($p = .48$). The mean increase of white oak basal area (7%) between the two entries was nearly double that of the red oak subgroup (4%). Twenty years after the first entry, the shade tolerant red maple subgroup was less than inventoried preharvest in the mature stand (4% versus 14%), but the undesirable subgroup occupied 17% in the regenerated openings compared with 5% in the preharvest stand.

Large trees (≥10 cm dbh class) in opening centers were dominated by the yellow-poplar subgroup and lesser stem densities in the two oak subgroups (Figure 7). Also present (not shown in Figure 7) in centers were species in the desirable subgroup (primarily sweet birch) consisting of 133 trees/ha in the two smallest dbh classes. In the periphery of openings, density of the yellow-poplar subgroup (152 trees/ha) was similar to stem density of the two oak subgroups (133 trees/ha), particularly for white oaks. The undesirable subgroup of species was represented in the edge position by 38 trees/ha (primarily sourwood) in the 10 cm dbh class. All red maple stems were ≤7.5 cm dbh.

Table 2. Mean density (standard deviation in parentheses), mean basal area and quadratic mean diameter breast height (dbhq) by position in openings, reproduction age, and species subgroups following two harvest entries in the mixed-hardwood stand of the Frothingham group selection study area.

Reproduction Age, Species Subgroups	Stem Density (n/ha)			Basal Area (m^2/ha)			Dbhq (cm)		
	Center	Edge	*p**	Center	Edge	*p*	Center	Edge	*p*
10-year-old openings (n = 14)									
Red oak	230 (383)	1,659 (2,012)	<.01	0.21 (0.63)	0.34 (0.48)	.04	1.12 (1.35)	1.22 (0.70)	.80
White oak	971 (1,955)	5,416 (7,969)	<.01	0.11 (0.34)	0.74 (1.32)	<.01	0.70 (0.23)	1.35 (0.64)	.01
Yellow-poplar	11,750 (6,541)	8,222 (11,855)	<.01	8.16 (5.57)	2.55 (3.68)	.04	2.88 (1.51)	2.03 (2.26)	.26
Other desirable	2,047 (2,438)	1,870 (2,022)	.71	1.98 (2.63)	0.39 (0.47)	.44	3.06 (1.70)	1.46 (0.60)	<.01
Red maple	971 (916)	2,047 (2,636)	.20	0.23 (0.36)	0.13 (0.15)	.40	1.34 (0.91)	0.81 (0.35)	.06
Other undesirable	*2,382 (3,974)*	*2,929 (3,080)*	*.41*	*0.73 (1.00)*	*0.39 (0.40)*	*.29*	*1.67 (1.11)*	*1.21 (0.63)*	.19
Overall subgroups	18,350 (6,962)	22,142 (11,168)	.29	11.42 (4.89)	4.53 (3.18)	<.01	2.94 (1.07)	1.61 (0.55)	<.01
20-year-old openings (n = 13)									
Red oak	551 (622)	646 (938)	.34	1.39 (2.83)	0.78 (2.05)	.86	2.45 (2.78)	1.72 (1.77)	.44
White oak	476 (617)	817 (1,142)	.20	1.86 (5.06)	1.51 (2.11)	.18	2.48 (3.43)	3.98 (4.45)	.36
Yellow-poplar	2,527 (1,984)	1,938 (2,334)	.26	10.26 (9.12)	3.05 (2.71)	.23	7.56 (5.05)	4.93 (4.20)	.17
Other desirable	1,539 (1,675)	1,406 (1,712)	.86	2.46 (2.80)	0.95 (1.76)	.75	3.43 (2.23)	1.93 (1.51)	.06
Red maple	1,406 (1,844)	1,121 (810)	.73	0.40 (0.80)	0.74 (1.22)	.04	1.42 (0.91)	2.06 (1.45)	.20
Other undesirable	1,121 *(965)*	1,273 *(1,192)*	.59	3.16 *(6.79)*	1.68 *(2.62)*	.73	3.47 *(3.02)*	2.89 *(1.80)*	.55
Overall subgroups	7,620 (2,844)	7,202 (3,610)	.74	19.54 (8.05)	8.70 (4.65)	<.01	5.87 (1.69)	4.10 (1.47)	<.01

*p determined from F statistic resulting from one-way analysis of variance of position in opening (center versus edge) by species subgroup and reproduction age class.

Figure 3. Effects of position in opening and trends of opening size on relative basal area of reproduction for six species subgroups 10 years after the 2005 entry. Relative basal area of species subgroups followed by an asterisk (red oaks, white oaks, yellow-poplar) were significantly ($p < .01$) influenced by position in the opening.

Figure 4. Box-and-whisker plots of yellow-poplar mean height of reproduction in relation to center and edge positions in openings at 10 and 20 years of age. The lower and upper whiskers of each box represent the minimum and maximum mean heights of trees in openings, the box ends are the 25 and 75 percentiles of mean heights, the solid line in the box is the median, and the dashed line is the mean tree height. Mean heights were significantly different ($p < .01$) between center and edge positions for both cohort ages of yellow-poplar reproduction.

Analysis of the two species groups combined as a community of reproduction, rather than individually as subgroups, revealed a significant change of dominance between the first and second decades of development (Table 3). Simpson's index of diversity increased (greater diversity) significantly ($p = .035$) for the openings overall, from 0.603 to 0.704. Diversity of species groups did not change at opening edges ($p = .141$) but increased significantly in centers ($p = .002$). Although the diversity index of the preharvest stand was greater than for the 20-year reproduction (0.881 versus 0.782), the preharvest and postharvest communities could not be statistically compared because of an incompatible data structure used for the mature stand inventory.

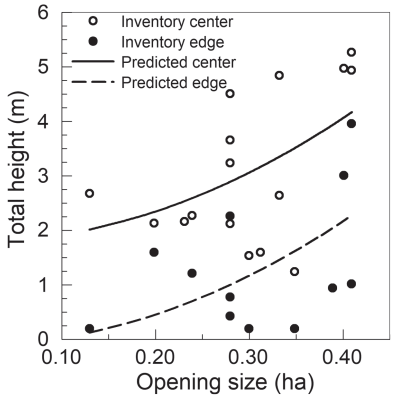

Figure 5. Inventoried and predicted mean total height of 10-year-old yellow-poplar reproduction in relation to the combined effects of opening size and center or edge positions.

Stem density of the combined reproduction subgroups in openings of both entries (Figure 2C), which attained a maximum dbh of 20 cm, was nearly six times greater than for the preharvest mature stand (Figure 2A). The regression of log10-transformed stems per hectare graphed as a function of 5 cm dbh classes for the pooled two cohorts of even-aged reproduction in the 1988 and 2005 entries displayed the linear form of a balanced distribution (Figure 2C). The regression value of Q (1.92) for the two combined age classes of reproduction was significant ($p < .01$, $R^2 = 0.999$).

Discussion

Following the failure of long-term management by single tree selection to recruit desirable reproduction in stands of upland Appalachian oaks (Della-Bianca and Beck 1985, Keyser and Loftis 2013), the Frothingham study was established in an adjacent stand to evaluate group selection harvests to achieve that goal. Before the first entry basal area composition of the mature stand consisted largely of approximately similar amounts of oaks (36%) and yellow-poplar (31%) (Table 1). Twenty years after the first entry postharvest reproduction composition in the small (0.10 ha) openings matched that present in the preharvest stand, except for absence of shortleaf pine, which was a remnant artifact of previous woodlot land use. Species basal area, however, shifted to dominance by yellow-poplar (47%) over oaks (20%), which can be partly attributed to a different disturbance regime following federal land acquisition associated with reduced woodland burning, and livestock grazing in particular. For example, the ranking of tree species favored by cattle for browsing (red maple < oaks < yellow-poplar) was likely a contributing factor resulting in reduced presence of yellow-poplar and increased establishment and survival of oaks (Biswell and Hoover 1945). Although mean stem densities ranged widely among the 13 openings of the 1988 entry and 14 openings of the 2005 entry, the diameter structure of reproduction for the combined openings displayed the (log10-transformed) reverse J-shaped curve of a balanced, uneven-aged stand (Figure 2C).

Opening sizes ranged from 0.05 ha to 0.41 ha for the 27 openings inventoried in the two entries of our study. We found no significant correlations of opening size alone with stem density or basal area of reproduction for any of the two species groups, a result that differs from findings reported in other group selection studies in mixed-hardwood forests. In a study of three opening areas (0.02, 0.16, 0.46 ha), 48 years after harvests in mixed upland oak stands, Lhotka (2013) reported greatest stem densities of yellow-poplar in the largest openings, oak in intermediate sizes and shade tolerant species in the smallest size. Minckler and Woerheide (1965) also reported greater densities of yellow-poplar in large openings (diameter greater than height of the surrounding stand) and oaks in smaller openings (diameter less than height of the adjacent stand). In a group selection study of six opening sizes (0.015–0.503 ha) in bottomland mixed-hardwood stands of South Carolina, Collins and Battaglia (2008) reported no optimum size for enhancement of oak reproduction but reported greater stem densities in the largest openings. Zhu et al. (2014), in a global metastudy, concluded there was no consistent optimum opening size favorable for oak reproduction. In agreement with Zhu et al. (2014), we were unable to determine an opening size most favorable for oak reproduction. It is evident from results of our study, however, that reproduction of desirable intolerant species, including oaks, can be obtained in openings as small as 0.05 ha in dry-mesic mixed-hardwood stands.

Position had a greater effect than opening size on density and basal area of several species subgroups, particularly oaks (Table 2). Density of oak reproduction was greater at edges of openings, compared with centers, which agrees with 10-year results from a group selection study reported by Holladay et al. (2006). In our study, stem density and basal area of white oaks were strongly associated with position and were five times greater at edges of openings than in centers. The red oak subgroup showed a similar relationship with opening position for density, but a weaker association with basal area. Shade-intolerant yellow-poplar was the dominant species in the centers of all openings. Distribution of the shade-tolerant undesirable group of species was not significantly associated with either the periphery or center of openings. Our findings agree with other studies reporting variable distribution of species in openings, likely as a response primarily to reduction of light resulting from shading by other species (Gottschalk 1994). In agreement with our results, Dale et al. (1995) and Collins and Battaglia (2008) reported greater density and basal area of oak reproduction at edges of openings than centers. As we observed and consistent with what has been observed elsewhere in the CHR, yellow-poplar can be the primary competitor to oak in group selection openings on dry-mesic sites, particularly in the center of openings (Smith 1977, Weigel and Parker 1997, Iverson et al. 2017). Trends of composition changes between 10 and 20 years (Figure 6), however, indicate decreasing density of yellow-poplar and reduction in the desirable subgroup primarily by sweet birch and black locust, as Beck and Hooper (1986) reported for a mesic clearcut site. During this 10-year interval basal area of the other subgroups approximately doubled, particularly for the undesirable subgroup of shade tolerant species. Noteworthy during this period were increases in relative basal area of the two oak subgroups, particularly by white oaks (from 5% to 12%) (Figure 6), which occurred in nearly all openings and particularly among trees of large dbhq (>10 cm) at edge positions (Figure 7). Although large oaks at edge positions were sparse (133/ha), we suggest this trend of reproduction development could be preliminary evidence in support of the

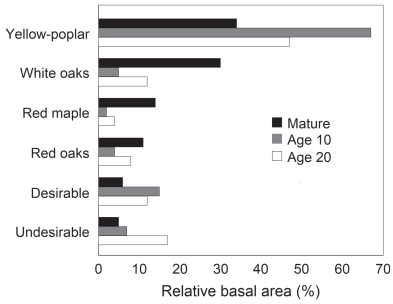

Figure 6. Proportion of total tree basal area ≥2.5 cm diameter breast height (dbh) by species subgroup in the mature mixed-hardwood stand before the first entry and in the regenerated openings after 10 years and 20 years.

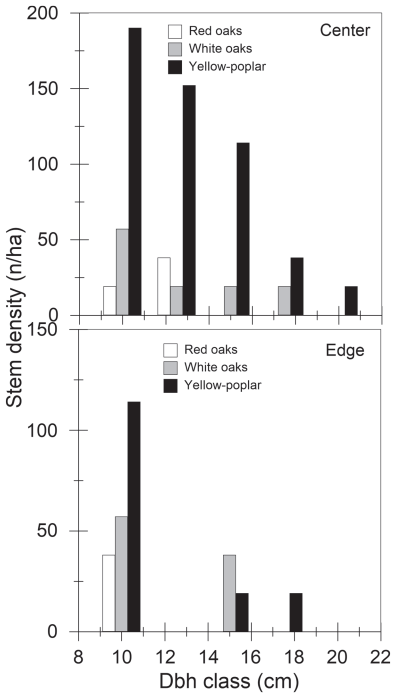

Figure 7. Distribution by 2.5 cm diameter breast height (dbh) classes of predominant species subgroups consisting of large trees (≥10 cm dbh) at the opening center and edge of 20-year-old reproduction of oak and yellow-poplar subgroups. Not included at the opening centers of the desirable subgroup were 133 stems/ha in the 10 and 12.5 cm dbh classes and at the edges of the undesirable subgroup were 38 stems/ha in the 10 cm dbh class.

delayed oak dominance hypothesis (Oliver 1978). Self-thinning by a pioneer species during the stem exclusion stage of stand development, however, is an alternative, simple explanation for changes of relative basal area occurring at a young age in the long-term development (100+ years) of this stand (Figure 6). The uneven-age diameter distribution pattern of the even-aged stems shown in Figure 7, however, offers a preview of their possible future composition in the Frothingham study area. Our second-decade results agree with early development dynamics of similar stands reported by Beck and Hooper (1986) at 20 years. Information on older development of mesophytic clearcut stands is sparse in the southern Appalachians, but 60-year results from a burned and salvage-cut old-growth forest (Della-Bianca 1983) suggest that much of our study area could eventually be dominated by a composition of yellow-poplar and mixed oaks, similar to the preharvest stand (Table 1).

Testing the delayed oak dominance hypothesis was an objective of our study, but we were unable to satisfactorily (statistically) accomplish that. Because a long-term study over a complete rotation would be required for a conclusive confirmation of the hypothesis, we were uncertain about the type of convincing supporting evidence needed from our short-term observations because results differed by opening position. Assuming that trees ≥10 cm form the intermediate and higher canopy in the 20-year-old openings, the opening centers were dominated by a 3:1 ratio of yellow-poplar to oaks (Figure 7). The predicted transition rate for change of crown class is low for oaks (Ward and Stephens 1994). This suggests little shift in species composition in the centers of openings of the future stand unless unfavorable climatic conditions (such as drought) results in slower growth or high mortality of yellow-poplar on submesic sites (Hilt 1985) or application of intermediate management treatments, such as crop tree release (Miller et al. 1994). At the edges of openings, however, the mean ratio of large (≥10 cm) yellow-poplar to oaks was approximately 1:1 and is likely to remain at that level or slowly change in favor of oaks with future stand development, which is in agreement with the hypothesis. In our study, however, site preparation and competition release treatments using herbicide three years after harvest were likely a contributing factor favoring the codominance of oaks with yellow-poplar, particularly around the edges of openings. Although a tenet of the hypothesis (shifting species dominance) has been addressed in a few studies in mixed-hardwood stands conducted during the stem exclusion stage (Morrissey et al. 2008), we found only one study that specifically addressed the hypothesis. Steiner et al. (2018) examined regenerated oak-red maple stands midway through rotations and reported variable support for the hypothesis among three ecoregions in central Pennsylvania and across a range of site qualities. They reported oaks were replacing red maple in the central Appalachian Mountains, particularly on dry-mesic sites, but the reverse was apparent in other ecoregions and on higher quality sites. Although we found no significant change in subgroup dominance (expressed as stem density) between the two age classes of reproduction in our study, changes in the total tree community were significant, which we suggest provides tentative support for the oak dominance hypothesis.

Table 3. Mean (standard deviation) Simpson's diversity index of the preharvest, mixed-hardwood stand and reproduction cohort ages resulting from two harvest entries by position in the group selection openings of the Frothingham group selection study area.

Position in Opening	Preharvest Stand	Harvest Entry (Cohort Age)		p*
		2005 (10 years)	1988 (20 years)	
Center	N/A**	0.429 (0.174)***	0.622 (0.108)	.002
Edge	N/A	0.602 (0.221)	0.702 (0.098)	.141
Overall	0.881	0.603 (0.147)	0.704 (0.782)	.035

*p determined from F statistic resulting from one-way analysis of variance of harvest entry date by position in opening.
**N/A, not applicable because of sampling design.
***Larger values of Simpson's index are associated with greater species diversity.

The response of reproduction in relation to the herbicide site preparation and followed three years by competition release treatments could not be evaluated because controls were lacking. As reported by Smith (1981) in mixed-oak stands of the central Appalachians, the herbicide treatments undoubtedly provided some benefit to survival and growth of reproduction in the preferred oak subgroups at 20 years of age and, hence, increased tentative support for the dominance hypothesis particularly in the periphery of openings during the near future. In our hypothesis tests, the chronosequence design of our study likely reduced sensitivity of the analysis to detect significant temporal changes of oak reproduction dynamics relative to yellow-poplar during the second decade of growth. Our results agree with findings reported by Beck and Hooper (1986) on permanent plots showing continued self-thinning of yellow-poplar and high survival of oaks after two decades of development in a clearcut, mixed cove hardwoods stand on a mesic site. Continued development of reproduction in the harvested openings suggests future composition like that of our preharvest stand (Table 1). Results from a long-term study of a severely burned and clearcut old-growth stand of cove hardwoods suggests initial dominance by yellow-poplar through 60 years for the Frothingham study with increasing codominance by oaks and a midstory of tolerant species (Della-Bianca 1983). Although previous influences of landscape scale fire and grazing have changed during the past century, other climate-related disturbance events (and possibly more intense than before) over the long rotation of these forests will continue to influence species composition.

Composition of reproduction varied widely among openings. Field observations suggested species distributions could be strongly affected by factors not quantified in our study, such as site quality, exotic species and disturbance during timber harvest. In the 1988 entry, for example, mesophytic yellow-poplar dominated the 12 openings that were located on dry-mesic slopes or on mesic sites along drainages. However, reproduction of yellow-poplar was absent from an opening on a ridge crest, possibly because of the likely xeric moisture regime there and lack of nearby seed sources. Dominant reproduction at that ridge site consisted of the oak subgroups, particularly chestnut oak, and hickories together with red maple and the undesirable subgroup. In another small opening on a mesic site harvested in 1988, the canopy was dominated by the nonnative, shade intolerant, light-seeded, tree-of-heaven (*Ailanthus altissima* [Mill.] Swingle) with a few yellow-poplar trees in the intermediate and codominant crown classes. This was a surprising finding because yellow-poplar had been "outcompeted" by an exotic species, for which there was no known seed source in the vicinity of the Frothingham study area and because tree-of-heaven is dioecious. Rebbeck et al. (2017) reported similar invasion by this exotic species following timber harvest in closed oak forests of southern Ohio.

Unusual site conditions resulting from harvesting possibly contributed to variation of reproduction in some openings of our study. For example, the mean ratio of yellow-poplar to oak density of reproduction in our study was 12:1 in centers and 2:1 at edges. In one of the 2005 openings, however, the ratio was 68:1 in the center and 0.29:1 at the edge. The low yellow-poplar to oak edge ratio in this second-entry opening could have resulted from a combination of two factors: edge effects from increased light admitted from an adjacent first-entry harvest that stimulated development of advance oak reproduction and lack of forest floor disturbance, which could have reduced but not eliminated germination of new and stored yellow-poplar seeds (Clark 1970). This opening was adjacent to a permanent logging access road that allowed felling of several mature perimeter trees into the opening edge followed by removal of the butt log with minimal soil disturbance from harvest equipment. The combination of a thick layer (~1 m) of logging slash from several large tree crowns and lack of soil disturbance in this edge sample plot apparently resulted in successful intraspecific competition within a large cluster of oak reproduction (observed present before the second entry) rather than interspecific competition with a dog-hair thicket of yellow-poplar saplings, which was present in the opening center. Sander and Clark (1971) also observed that basal sprouts from oak advance reproduction crushed by logging residues can emerge and grow rapidly in height.

The response variable of yellow-poplar height was significantly, directly associated with opening size only in the presence of center or edge position and only for the relatively large openings formed during the 2005 harvest (Figure 5). The quadratic effect of opening size in our model agrees with Sander and Clark (1971) who provided a curvilinear relationship of the area shaded by the adjacent forest in relation to opening size. Where timber production is a regeneration priority, Sander and Clark (1971) suggest a minimum opening size of 0.2 ha to reduce edge effects on growth of intolerant species. In agreement with our results, Smith (1977) reported better height growth of yellow-poplar as opening size increased from 0.018 to 0.45 ha and better growth in centers of openings compared with edges.

Several design issues weakened findings from our study. A design with increased power to detect effects of opening size could have resulted from harvest of replicated fixed areas rather than variable sizes, as in our study. Lack of preharvest inventories in openings reduced our ability to assess competition with focal species (oaks) by specific shade tolerant competing species, such as red maple. In retrospect, sampling edges of openings in a random direction increased variability of inventory data and did not allow testing of effects of aspect on reproduction, which was significant in the CHR north of the Ohio River (Weigel and Parker 1997, Morrissey et al. 2008). In the central Appalachians, however, Smith (1977) reported no effect of aspect on reproduction. We avoided placing edge samples next to logging roads to reduce effects of increased side light on reproduction in openings. Except for the instance mentioned above, however, we failed to note if edge plots sampled in the second entry were adjacent to openings created by the first entry. Also, an estimate of site index from each opening could have been useful to account for variation in some response variables, such as basal area of the yellow-poplar subgroup. Finally, our study used a chronosequence design to detect temporal trends of reproduction development at two stand ages, which introduced site and climatic related variation that would not have been present with permanent plots established in the first entry. We suggest the deficiencies in our study should be considered for addressing in future investigations, particularly increased sample size using permanent, paired center/edge plots on cardinal directions.

Effects are unknown concerning the herbicide release treatment three years after harvest on growth of desirable species, primarily the oak subgroups. Given the rapid growth of

yellow-poplar observed in this study and the characteristically slow height growth of small oak reproduction, beneficial effects of the herbicide release treatment could have been minimal, particularly in opening centers with high seedling densities yellow-poplar. The site preparation herbicide treatment of stumps, however, was apparently beneficial because red maple and other prolifically sprouting species (sourwood) were minor components of the inventoried reproduction; Smith (1981) reported similar results from herbicide site preparation treatments in West Virginia. The efficacy of herbicide release treatments on targeted reproduction development has not been widely evaluated in group selection harvests and could be a subject of evaluation in the next entry of the Frothingham group selection study.

Results from our study suggest group selection can be used to regenerate mature, mixed-hardwood stands with reproduction of desirable intolerant species, primarily with yellow-poplar but also with a small component of oaks. Stand management by group selection, however, requires additional administrative investment compared with conventional even-aged methods. For example, the harvesting access road system will be used for each entry and should be designed before the first entry to avoid disturbances to existing regenerated openings in future entries, which occurred in one opening of the Frothingham study. Detailed mapping of opening locations is desirable for distribution of harvests throughout the stand to meet wildlife habitat and visual objectives. Minimum sizes of openings must be considered for economics of harvest operations. For example, based on predicted crown sizes, an opening of 0.05 ha could include one tree in an oak subgroup with dbh of 152 cm or approximately 12 trees averaging 30 cm dbh (Bechtold 2003). Conventional opening size is a width about twice the height of the adjacent forest (Miller et al. 1994). Forest height in the Frothingham study area averaged about 33 m, resulting in an opening width of 66 m and size of about 0.34 ha. Larger opening sizes are considered patch clearcuts but achieve the same management objective of an uneven-aged stand structure consisting of three or more cohort ages (Miller et al. 1994). In central Appalachian mixed-hardwood stands, Smith (1981) recommended 0.20 ha as the minimum size to obtain satisfactory density of oak reproduction and adequate diversity of other desirable intolerant species. Additional information on implementation of uneven-aged management using the group selection method in Appalachian oak stands is provided by Miller et al. (1994).

Conclusions

Preliminary results from this long-term study show reproduction in 10- and 20-year-old openings consisted largely of intolerant yellow-poplar and lesser, about equal amounts of midtolerant oaks and tolerant undesirable species. Opening size, which ranged from 0.05 to 0.41 ha, had no effect on stem density or basal area of reproduction in any of the six subgroups of species. Position in openings, however, strongly affected species composition of reproduction with yellow-poplar dominating centers and codominating edges with oaks. During the second decade of reproduction development, basal area of the yellow-poplar and desirable subgroup (largely sweet birch and black locust) decreased while the proportion of other species subgroups increased, particularly oak and undesirable species subgroups. Our results suggest that composition of reproduction in openings as small as 0.05 ha can consist of desirable intolerant species, but the administration and economics of operational harvesting of only small openings could be questionable. Although an abundance of small openings could affect economics of harvesting using group selection, their distribution within stands could be important to achieve nontimber management goals, such as aesthetics and wildlife habitat. Also, we reported that stem diameters of 10- and 20-year-old even-aged reproduction followed a balanced, uneven-aged distribution, which was a technical concern by some early opponents of group selection. Early results from this long-term, operational-scale study suggest that group selection can be a viable method of uneven-aged management in dry-mesic southern Appalachian mixed-hardwood forests.

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