Forest Ecology and Management 586 (2025) 122701

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

The 10-year response of natural northern red oak reproduction to strip clearcutting an Appalachian hardwood stand

Patrick Plaugher *, Jamie Schuler

School of Natural Resources and the Environment, West Virginia University, Morgantown, WV, USA

ARTICLE INFO

Keywords:
Oak advance reproduction
Regeneration
Northern red oak

ABSTRACT

There are well-known difficulties associated with regenerating oak stands throughout the Central Hardwoods region. To successfully regenerate oak, competitive sources of advance reproduction are required ahead of harvesting—a condition that is rarely present, especially on productive sites. While treatments that enhance seedling competitiveness (*e.g.*, midstory removals, burning, competing vegetation control) are available, in practice, these are rarely implemented and/or effective because of high treatment costs and/or because they require delaying harvest.

As a potential alternative practice, we report the 10-yr results of a strip clearcut reproduction method that removes alternating 45.7 m wide strips across a mixed Appalachian hardwood forest, where the initial harvested strips provide timber revenue while simultaneously elevating understory light levels to increase oak seedling size within the residual strips to increase oak presence in a future harvest.

After 10 yr, we found that strip clearcutting facilitated the development of competitive northern red oak (*Quercus rubra* L.) advance reproduction within the residual strips. Northern red oak seedling densities (>10,000 stems/ha) were greater than any other species. Northern red oak seedlings were most competitive within the interior 11.4 m positions in the residual strips, while the high densities of competitive northern red oak seedlings along the edges of the residual strips were also associated with competitive black birch (*Betula lenta* L.) and black cherry (*Prunus serotina* Ehrh.) reproduction. By contrast, in the cut strips, black birch and yellow-poplar (*Liriodendron tulipifera* L.) were the dominant stems and oaks were almost nonexistent.

1. Introduction

Oaks are keystone species in the eastern United States and throughout the Appalachians. Upland oak forest types cover about 60 million hectares (150 million acres) of eastern forests, and the central Appalachian Mountains have some of the highest oak densities in the U. S. (McWilliams et al., 2002). Oaks are valued as a source of habitat and food for wildlife, as a timber species, and for provisioning ecosystem services and cultural benefits (Frankel et al., 2022).

Oaks have been declining across the eastern U.S. (Hix and Lorimer, 1991; Nowacki and Abrams, 1992). While they still dominate the upper canopy, oaks have been replaced in the seedling, sapling, and midstory layers, which suggests an inability to successfully recruit (Fei et al., 2011; Widmann et al., 2011). This failure in oak regeneration is due in part to the exclusion of fire and the subsequent "mesophication" of eastern forests (Alexander et al., 2021: Nowacki and Abrams, 2008). Fire exclusion has resulted in the densification of forests by shade-tolerant mesophytes whose traits create poor conditions for frequent, low severity fire, to which oaks are adapted (Alexander et al., 2021; Nowacki and Abrams, 2008). As a result, understory light conditions (less than 5 % full sunlight) are not conducive to the survival and growth of oak seedlings (Brose, 2008; Patterson et al., 2022) but instead favor shade-tolerant species in the absence of disturbance or opportunistic species following canopy disturbance (Alexander et al., 2021; Iverson et al., 2017).

The presence of competitive advance reproduction prior to overstory removal is usually required to successfully regenerate oaks (Dey et al., 2008; Loftis, 2004; Sander et al., 1976). To create competitive oak advance reproduction (seedlings >0.91 m (3 ft) tall) (Brose et al., 2008), treatments that create understory light conditions conducive to oak seedling development (full sunlight between 12 % and 30 %) (Brose and Rebbeck, 2017; Craig et al., 2014; Gottschalk et al., 1985; Miller et al., 2004; Miller et al., 2017; Patterson et al., 2022; Rebbeck et al., 2011) are recommended prior to overstory removal (Schuler et al., 2017).

* Corresponding author.
E-mail addresses: Jamie.Schuler@mail.wvu.edu, pap0021@mix.wvu.edu (P. Plaugher).

https://doi.org/10.1016/j.foreco.2025.122701
Received 6 November 2024; Received in revised form 20 March 2025; Accepted 26 March 2025
Available online 9 April 2025
0378-1127/

However, commonly suggested treatments (*e.g.* midstory removal, herbicide application, prescribed fire) can be hindered by high costs (Bailey et al., 2011; Rathfon, 2011) or other barriers such as restrictions on burning (*e.g.* Evans et al., 2018), perception of chemical use (*e.g.* Huffman, 1983), or the need for immediate income. Even when treatments are applied, there needs to be a willingness to allow enough time for seedlings to attain competitive sizes (*i.e.,* delayed harvest for 5–10 years).

Strip clearcutting is a possible alternative regeneration method to improve the chances of successfully regenerating oak. In our cases, alternative cut and leave strips provide a trade-off between managing understory light conditions in the residual stand and providing upfront revenue in the harvested cut strips (Schuler et al., 2017). Strip clearcuts are easy to mark and harvest, which can increase efficiencies and reduce logging damage to residual overstory trees.

When carried out properly, strip clearcutting creates a light gradient where the centers of cut strips have the greatest amount of light and the centers of the residual strips have the least light (Schuler et al., 2017). The cut strips will generally promote fast-growing hardwoods such as yellow-poplar (*Liriodendron tulipifera* L.) and therefore the residual strips will be the major source of oak for the next cohort (Schuler et al., 2017). When strips are oriented north-south, light penetrates into the residual forest from the sides as the sun progresses from east (morning hours) to west (afternoon hours) (Marquis, 1965). This penetration of light into the forest edge and residual stand increases light levels at the forest floor and affects the development of oak seedlings (Patterson et al., 2022). The residual strips should experience increased light levels for a period of 5–10 years, thereby enhancing the development of oak seedlings. Once seedlings reach competitive size the residual strips can be harvested to fully release the developed oak understory.

Strip clearcutting is a somewhat novel practice for regenerating oak in Appalachia. Intuitively light availability will increase throughout cut and residual strips following a gradient of high to low from the center of cut strips to the center of residual strips. The increased light availability should positively affect oak seedling development along strip edges and within residual strips. However, we expect high light availability within the cut strips to stimulate the growth of shade intolerant competitors, hindering oak seedling development. We report the effects of position within cut and residual strip pairings on the development of natural regeneration 10 years after the harvest of the initial strips.

2. Methods

2.1. Study site

The study site was located in the central Appalachian Mountain region on the West Virginia University Research Forest in Preston County, West Virginia, USA. The study site has a north-facing aspect with 20 percent average slopes. The site index was estimated to be 21–23 m (base age 50) for upland oak using site index curves from Schnur (1937). Soils were estimated as Dekalb channery sandy loam (Soil Survey Staff, 2024). Overstory species composition prior to harvesting was largely yellow-poplar, northern red oak (*Quercus rubra* L.), black cherry (*Prunus serotina* Ehrh.), and red maple (*Acer rubrum* L.), representing 66 %, 21 %, 5 %, and 3 % of the harvested volume (in 2014) and 55 %, 21 %, 6 %, and 13 % of the basal area, respectively. The study site is roughly 14 ha in size, harvesting occurred in the early summer and fall of 2014 (Fig. 1) coinciding with an anecdotally better than average year for northern red oak acorn production. Yellow-poplar, black cherry, red maple, and black birch (*Betula lenta* L.) are capable of accumulating seed within the seed bank and seed sources for these species were represented across the elevational gradient on the site. Although we did not measure seed fall it was assumed that each species had ample seed sources and opportunity to establish. Strips were 45.7 m wide (roughly 1.25 times the height of the canopy) and oriented in a north-south direction. All stems > 2.5 centimeters (1 in) diameter at breast height were hand-felled and merchantable material extracted with rubber-tired cable skidders.

Fig. 1. The study site following the initial strip harvest (U.S. Geological Survey, 2016).

2.2. Field measurements

Regeneration plots were measured across the site beginning in May 2024, ten years after one-half of the strips were harvested. Plots had a 1.8-meter radius and all tree species greater than 15 cm tall were counted and placed into 0.3-meter height classes. All species present in the plots were tallied, but our analysis focused on the most abundant species. Northern red oak stems greater than 0.91 m in height were considered competitive based on the recommendations of Brose et al. (2008). Within residual strips trees with a DBH greater than 7.6 cm were considered residual stems and excluded from the count.

Plots were placed in each of eight positions within each residual-cut strip pairing that represented a gradient of light conditions (Fig. 2). Four separate strip pairings were used as replicates and plots were blocked by slope location (low, intermediate, and upper). There were 24 plots within each slope position (Fig. 2) resulting in 72 plots per strip pairing and a total of 288 plots. Plots were placed in the inner 4 strip pairings of the stand (Fig. 1) and at least 7.5 m away from skid roads to avoid the effects of soil disturbance.

Position 1 represents the edge of the residual strip receiving morning light (a.m. edge), position 5 represents the edge of the residual strip receiving afternoon light (p.m. edge), positions 2 and 4 represent one-

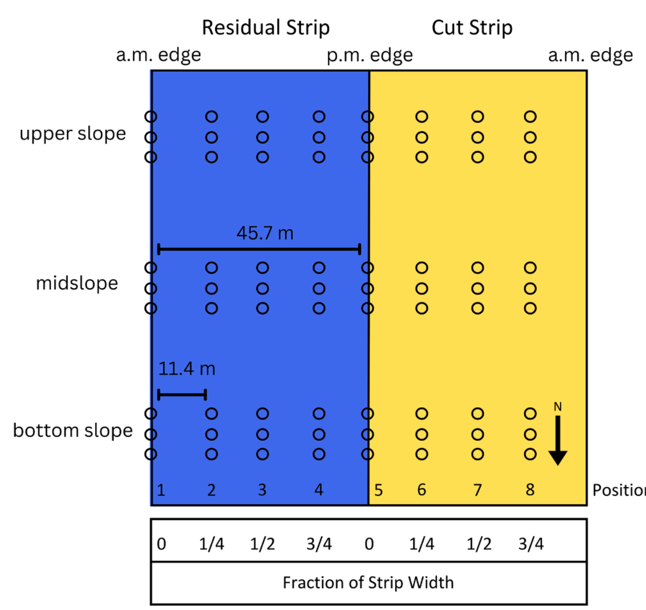

Fig. 2. Layout of one slope-strip pairing replicate of regeneration plots. This block of plots represents 1 strip-pairing block.

quarter of the way into the residual strip, and position 3 is halfway into the residual strip. Similarly, positions 4 and 6 are one-quarter into the cut strip, and position 7 represents halfway into the cut strip.

Photosynthetically active radiation (wavelengths of light between 400 and 700 nm) (PAR) was measured using an ACCUPAR LP-80 sensor (METER Group, Inc., San Francisco, CA, 2024) 1 m above the ground in July 2024 on a completely cloudless day (July 2) between 10 a.m. and 2:30 p.m. Five instantaneous readings were taken consecutively at each plot and averaged. Full sunlight reference measurements were taken simultaneously in an open area adjacent to the stand. PAR was also measured in 2016, 2 years after the initial harvest. Measurements in 2016 were taken using the same methods as in 2024, although not necessarily at the same locations.

2.3. Data analysis

Regeneration data were analyzed as a randomized block ($n = 4$) design with subsampling (9 plots per position per replicate). The four strip pairings represented the four replicates. Analysis of variance (ANOVA) was used to examine differences in positions and among species. Statistical tests were conducted using alpha value = 0.05 level of significance.

Two generalized linear mixed models using negative binomial distributions were used, the first tested the effect of position on the stems/ha of competitive northern red oaks across the residual and edge positions (positions 1–5). Position was used as the fixed effect in the first model while slope position, and subsample were used as random effects. The second model was used to test the effect of species on the stems/ha of competitive northern red oak and black birch across the residual and edge positions. Black birch and northern red oak were the only species tested to simplify Tukey's tests and black birch was the most important competitor across the residual strips. Species was used as the fixed effect in the second model while slope position, subsample, and plot were used as random effects. We used a Tukey's test on least squares means to test the differences between treatment levels.

A one-way ANOVA using a beta distribution was utilized to test the effects of position on percent full sunlight in 2016 and 2024 separately. A Tukey's test on least squares means was utilized to separate differences between treatment levels.

The R statistical software (R Core Team, 2024) was used to analyze data, the package glmmTMB was utilized to create ANOVA models (Brooks et al., 2017), and the package emmeans was used to carry out Tukey's tests (Lenth, 2024).

2.4. Dominance probabilities

The number of seedlings required to successfully regenerate dominant and codominant oaks was calculated based on Loftis's (1990b) dominance probabilities. Dominance probability equations are based upon the quality of the site (site index) and the root collar diameter of the seedlings. We estimated the root collar diameter (RCD) of tallied northern red oak seedlings based on height. Using the classes described by Brose et al. (2008), stems between 0.15 and 0.91 m have an RCD of 1 cm and stems with a height greater than 0.91 m have an RCD of 1.9 cm. A stocking target of 20 % was set based on the initial basal area of northern red oak present in the stand prior to harvesting. Using Gingrich's stocking equation (1967), 363 oak trees/ha are needed at age 20, when the average stand diameter is 7.6 cm. Dividing the desired number of dominant oaks at age 20 (363 trees/ha) by the dominance probability of different seedling size classes yields the required number of seedlings for successful regeneration.

3. Results

3.1. Photosynthetically active radiation

PAR measurements taken in 2016 (second growing season after initial harvest) show distinct differences in light levels by position within the strip pairs (Fig. 3). PAR levels ranged from 11 % to 73 % of full light across all positions. Clearly, harvest strips had higher PAR levels, but levels of PAR in different positions within cut and residual strips were different (Fig. 3). Position significantly affected percent full sunlight (Chisq=73.046, df=7, $p < 0.0001$). The edges and the cut strip had significantly greater full sunlight than the center of the residual strip. The a.m. edge and cut strip also had significantly greater full sunlight than the one -quarter and three-quarter positions (quarter positions) of the residual strip.

Light measurements collected in 2024 reveal a distinct drop in PAR from the 2016 levels (Fig. 3). Every position except the a.m. edge (13 % of full sunlight) had full sunlight below 6 %. Position significantly affected percent of full sunlight (Chisq= 26.385, df=7, $p < 0.0005$). Due to the high variance in measurements, the a.m. edge was only significantly greater than the cut strip (positions 6, 7, 8). Low PAR levels in the cut strips reflect measurements taken below a well-established canopy of the ten-year-old tree saplings.

3.2. Regeneration

Regeneration analysis was focused on northern red oak (NRO), black birch (BB), yellow-poplar (YP), black cherry (BC), and red maple (RM) as they constituted 94.4 % of all trees counted out of 21 different species tallied. Northern red oak was the most common species with > 10,000 trees/ha across the entire stand. However, more than 75 % of these stems were noncompetitive (<0.91 m tall) (Table 1).

As expected, the cut strips regenerated mostly to non-oak species; yellow-poplar, black birch, and black cherry were very common (Fig. 4). Yellow-poplar had the greatest stem density across the cut positions followed closely by black birch.

Competitive black birch and northern red oak stem densities were not statistically different along edges, however the trends suggest slightly higher stem densities of black birch at edge positions. There was a decline in density of competitive stems across all species from the

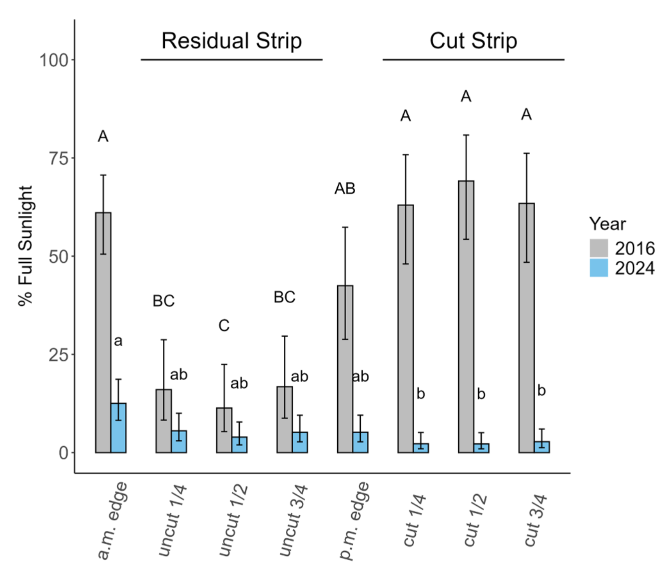

Fig. 3. Least squares mean % full PAR at the different positions within the strip clearcut 2 yrs (gray) and 10 yrs (blue) after treatment. Error bars represent 95 % confidence intervals. Values with different letters denote significant differences.

Table 1
Stem density (trees/ha) of the five most common regenerating species by height class for the entire stand. One standard error is represented below means.

		Height Class (m)						
Species		< 0.3	0.31–0.91	0.911–1.5	1.51–3	3.1–4.6	4.61–7.6	> 7.6
BB	Mean	327	1070	449	796	687	842	145
	SE	± 49	± 119	± 63	± 91	± 89	± 104	± 28
BC	Mean	380	469	198	327	231	426	158
	SE	± 65	± 73	± 42	± 61	± 41	± 60	± 32
NRO	Mean	4051	5165	925	459	92	9	0
	SE	± 537	± 498	± 122	± 68	± 20	± 7	± 0
RM	Mean	1774	839	92	52	69	99	56
	SE	± 197	± 118	± 22	± 16	± 21	± 26	± 22
YP	Mean	380	865	330	783	614	723	49
	SE	± 77	± 184	± 63	± 129	± 101	± 104	± 14
Other	Mean	439	360	82	313	105	82	33
	SE	± 66	± 43	± 24	± 74	± 24	± 23	± 13

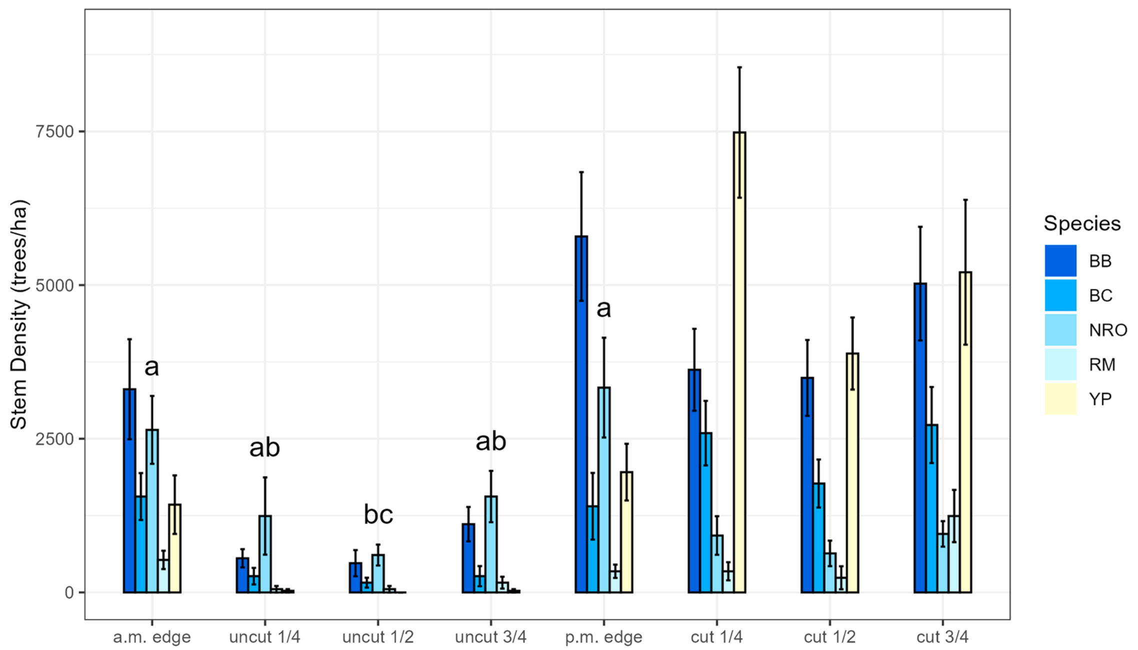

Fig. 4. Stem density of competitive stems (>0.91 m tall) for the 5 most common regenerating species across the cut and residual strip pairings. Error bars represent 1 standard error. Letters are associated with NRO in positions 1–5 and denote significant differences among treatments.

edges towards the center of the residual strips (Fig. 4).

Competitive stems of northern red oak and black birch outnumbered the competitive stems of other species within the interior of the residual strips (Positions 2–4) (Fig. 4). Northern red oak was most competitive within the interior of the residual strips as there was a greater number of competitive oak stems and less competition from other species in comparison with the edge and cut positions. Within residual strips there were roughly 608, 1242, and 1559 competitive stems/ha in center, one-quarter, and three-quarter positions, respectively (Fig. 4). Competitive northern red oak was significantly more abundant along the edge positions compared to the center of the residual strips ($p < 0.003$) (Fig. 4). There were no significant differences between competitive black birch and competitive northern red oak stems/ha within the residual strips ($p = 0.783$ 3).

We recorded the dominant species (by height) on each plot and summarized the data by position (Table 2). Black birch dominated the highest percentage of edge and cut plots. Yellow-poplar and black cherry were the second and third most common species dominating edge and cut plots, respectively. Northern red oak dominated the highest percentage of plots in the residual strips (39 %) (Table 2). However, northern red oak dominated only 8 % of plots in edge positions and nearly 0 % of plots in cut positions.

Table 2
Percent of plots with each species as the dominant tree (by height) for the top 3 species of each position grouping.

Residual Strip		Edge Positions		Cut Strip	
Species	%	Species	%	Species	%
NRO	38.9	BB	57.3	BB	37.6
BB	33.6	BC	17.3	YP	29.4
BC	10.7	NRO	8.0	BC	18.4

Despite their dominance throughout the residual strips, most oak seedlings were relatively small. Roughly one-half of the plots dominated by an oak stem in residual strips were comprised of individuals less than 0.91 meters tall.

3.3. Dominance probabilities

Using Loftis' (1990b) dominance probabilities for oak reproduction to become dominant or codominant 20 years following overstory removal, stems between 0.15 and 0.91 m tall have a 0.065 probability of dominance and stems > 0.91 m tall have a 0.19 probability of dominance in a stand with a site index of 21 m at base age 50 (for upland oaks). Under these conditions it would take roughly 5585 stems/ha between 0.15 and 0.91 m tall to reach desired stocking or roughly 1911 stems/ha > 0.91 m tall to reach desired stocking. Required stem densities for different size classes and the stem densities of different size class northern red oaks for positions 1–5 are summarized in Table 3.

Both edge positions would have adequate densities of northern red oak advance reproduction as both positions have > 1911 stems/ha > 0.91 m tall (Table 3). Both quarter positions and the center of the residual strip have sufficient densities of advance reproduction as the density of stems between 0.15 and 0.91 m tall is greater than the estimated required amount. Even removing stems < 0.3 m tall all residual positions still have sufficient stems/ha of advance reproduction based on this estimation. Also considering the combined density of stems between 0.15 and 0.91 m tall and stems > 0.91 m tall all residual positions have beyond the required density of reproduction for regeneration success.

4. Discussion

The strip clearcut approach used here was intended to provide a compromise between oak regeneration and landowner income. The cut strips provided immediate income but very little control of reproduction. The residual strips were designed to cultivate oak advance seedlings. After ten years there were few oak seedlings within the cut strips. Furthermore, the very few oak stems that were in the cut strips were dominated by black birch, yellow-poplar and black cherry. Yellow-poplar, black birch, and black cherry were favored by the initial high light intensities (Fig. 3) within the cut strips and their relatively fast growth under full light conditions.

Although yellow-poplar and black cherry were well represented in the cut strips (Fig. 4), black birch trees were taller on average, occupying the most dominant crown positions (Table 2). Economically, black cherry and yellow-poplar are valuable hardwood species in Appalachia, while black birch generally has low commercial value and is often considered a less desired species. Black birch generally does not reach heights greater than 21–24 m and is commonly a midstory inhabitant (Lamson, 1990). Black birch gains height very rapidly immediately following canopy release (Fei et al., 2005) but slows down after roughly 40 years (Lamson, 1990). Yellow-poplar and black cherry generally attain heights of roughly 27.5–30.5 m in 50 years on sites of similar quality to the study area (Beck et al., 1990; Beck and Della-Bianca, 1981; Marquis, 1990).

It is possible that the yellow-poplar will overtop the black birch as stand development continues. We suspect that the currently dominant black birch may act to thin the suppressed yellow-poplar. Continued monitoring of this study will reveal whether black birch remains a dominant member of the overstory canopy or if it will fall behind the fast growing yellow-poplar and black cherry within the initial cut strips.

Based on dominance probabilities and the target of 20 % stocking of dominant and codominant oaks there were adequate densities of northern red oak advance reproduction to regenerate the residual strips. Roughly 20 % of plots within residual strips were dominated by an oak of competitive size. However, there were also high densities of competitors within residual strips. Black birch was the most common and dominant competitor for oak along the edges and the interior of the residual strip, though black cherry was also an important competitor along the edges (Table 2).

Light levels along the edges were quite high (40–55 % of full sunlight) two years after the first strips were harvested (Fig. 3). These levels are higher than the 12–30 % recommended for oak seedling development (Gottschalk et al., 1985; Loftis 1990a). This stimulated the growth of competitors, especially black birch, as the edges were the only positions within the residual strips where competitive oaks were outnumbered by any single other species (Fig. 4). Although the edge positions have high numbers of black birch and black cherry, the very high density of larger oak stems along the edges makes it likely that some of them will attain dominant canopy positions.

The light levels of the quarter positions following the initial harvest were within the recommended range of light for oak seedling development (15–17 %) (Fig. 3). Regeneration most favors northern red oak along the quarter positions. Although there was not a significant difference between black birch and northern red oak regeneration densities within the residual strips, the quarter positions held the greatest disparity between northern red oak and black birch in the favor of oak (Fig. 4).

The center of the residual strip had the lowest density of competitive oak stems (608 stems/ha) (Fig. 4) and the light levels following the initial harvest were lower than recommended (10 %) (Fig. 3). This light level was likely too low to fully benefit oak seedling development. Although competitive northern red oak advance reproduction in the center of the residual strip is similar to the amount of black birch reproduction and outnumbers the reproduction of all other species, new seedlings of opportunistic competitors (yellow-poplar and black cherry) could become established and outcompete oak reproduction following overstory removal.

One possible solution to reduced light levels in the center of residual strips would be to reduce the residual strip widths to allow more light infiltration to the center. Although light along the quarters was within recommended levels it could increase further within that range and light along the center should increase to properly benefit oak seedling development. Our data as well as others (*e.g.*, Patterson et al., 2022) show greater than 10 % of full light levels 10–12 m away from gap edge and less than 10 % of full light levels beyond that distance, which is more consistent with closed-canopy forests.

Black birch was the most important competitor with northern red oak across the residual strips. Understanding how black birch and northern red oak may interact as stand development continues will be very important to recruiting dominant oaks. Oliver (1975) found that oak can catch up to and overtop initially dominant black birch and red maple following intense canopy disturbances (such as a clearcut). Although there are important differences between our study site and those studied by Oliver (New England vs. Central Appalachian location, site index, and preharvest overstory and understory conditions) the silvical characteristics of northern red oak and black birch could support this possibility.

Oaks are drought adapted species which first build large root networks before putting energy into aboveground shoot growth (Johnson et al., 2002), if several drought events were to occur following harvest oaks would be less affected by moisture stress and could likely attain dominance over the less drought resistant black birch (Daley et al., 2007; Lamson, 1990; Turnbull et al., 2002; Vivin et al., 1993).

The understory light levels in 2024 (Fig. 3) were extremely low in every position (<6 % full sunlight) except the a.m. edge (13 % full

Table 3
Northern red oak stem density by size class and position compared to the required stem density for regeneration success based on dominance probabilities. One standard error is represented below means.

size class		required	a.m. edge	uncut 1/4	uncut 1/2	uncut 3/4	p.m. edge
0.15–0.91 m	Mean	5585	11,581	11,131	16,393	22,316	10,127
	SE		± 2125	± 2081	± 3249	± 4372	± 2526
> 0.91 m	Mean	1911	2644	1243	608	1560	3331
	SE		± 552	± 629	± 170	± 417	± 812

sunlight). Understory light levels will decrease with time as side shading increases from the regenerating cut strips. These decreasing light levels create declining conditions for oak seedling development. Waiting longer than 10 years after the initial strip harvest to remove the residual strips could reduce the amount of competitive oak reproduction due to these decreased light levels. Additionally, when implementing an ideal strip clearcut, acorn crops should be monitored prior to any harvesting and implementation of the initial strips should take place after a bumper crop of acorns so that an abundance of new oak seedlings is present.

Our study was restricted to a single site and therefore interpretation of our results should be restricted to similar sites within the central Appalachians. Our site had a site index of roughly 21–23 m for upland oaks, was located on north facing slopes, and had a pre-harvest overstory composition of roughly 55 % yellow-poplar and 20 % northern red oak with lesser amounts of red maple and black cherry. Sites like this are common throughout the Central Appalachian region.

Site productivity (related to soils and topographic position) and overstory composition prior to harvest will affect the establishment of seedlings within cut and residual strips. Oak reproduction can more readily accumulate on lower quality sites, as such more light can be made available without stimulating the growth of shade intolerant competitors such as black cherry or yellow-poplar due to water availability becoming restricting. On higher quality sites it is likely that strip widths may need to be narrower to avoid stimulating yellow-poplar establishment (Loftis 1990b). A commercial thinning targeting the removal of yellow-poplar from the overstory well in advance of initiating the strip clearcutting regeneration method could help to reduce the seed source of yellow-poplar.

In areas with little or no presence of yellow-poplar (uncommon in Central Appalachia) it is likely that smaller oak advance reproduction can have a greater chance at competition. This is due to the extremely fast growing newly established yellow-poplar seedlings being absent post-harvest. On sites with a dense midstory of shade tolerant competitors such as red maple or American beech (*Fagus grandifolia* Ehrh.) competition control treatments may be necessary to establish oak reproduction. Our stand experienced high densities of black birch reproduction despite taking up a small portion of the preharvest overstory composition. In areas without an abundant response of black birch reproduction oak seedlings will be more competitive.

On south or west facing sites, site quality tends to be reduced thereby reducing competition from fast-growing mesic species (*e.g.* yellow-poplar). However, on S-W facing sites with high site indices manipulation of light availability needs to be careful, south facing slopes will receive a greater amount of light relative to north facing slopes which could stimulate the growth and establishment of shade-intolerant competitors. As well on east or west facing slopes with extreme slopes, the slope effect on shadow length could result in different light availability between eastern or western edges of strips.

Further research on strip clearcutting to regenerate oaks should be carried out on sites with different productivity levels, different aspects, and different overstory compositions and should experiment with changing residual and cut strip widths. As well further research needs to be carried out within different geographic regions to better understand how this harvesting method can regenerate oak species.

5. Conclusions

Compared to clearcutting (conditions similar to cut strip positions), strip clearcutting seems to offer a reasonable compromise between income generation, ease of implementation and regeneration of oak species. Strip clearcutting increased understory light levels within the residual strips to levels benefiting oak seedling development. Competitive advance oak reproduction was cultivated throughout the residual strips (positions 1–5), although oak seedlings experienced the least competition at 11.4 m into residual strips from strip edges. Based on the dominance probability estimates and the abundance of northern red oak seedlings, there appears to be sufficient quality and quantity of oak advance reproduction to regenerate northern red oak to its pre-harvest stocking within residual strips.

Follow-up competition control treatments could be used during the regeneration process to further enhance oak reproduction. Although no additional treatments were conducted within the cut or residual strips, controlling competing herbaceous and woody vegetation may provide additional resources to accelerate oak seedling survival and development. Similarly, manipulating strip widths, both residual and cut, can influence light levels. Depending on the oak species and competing tree species present on the site these strip widths may need to change.

The residual strips were harvested following sampling in 2024. Continued monitoring is needed to determine if the advance reproduction cultivated since the initial harvest will be sufficient to recruit stems into dominant canopy positions after the harvest of the residual strips.

Funding

This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, McIntire Stennis project under WVA00804.

CRediT authorship contribution statement

Schuler Jamie: Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Plaugher Patrick:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Thank you to the WVU Research Forest staff, Robert Driscole and Michael Boyce for their assistance with the layout and logistics of implementing the harvest. Thank you to Dr. Kirsten Stephan and Dr. Melissa Thomas-Van Gundy for editorial comments.

Data Availability

Data used in this publication is part of an ongoing study and as such cannot be made available at this time.

References

Alexander, Heather D., Siegert, Courtney, Brewer, J.Stephen, Kreye, Jesse, Lashely, Marcus A., McDaniel, Jennifer K., Paulson, Alison K., Renninger, Heidi J., Varner, J.Morgan, 2021. Mesophication of oak landscapes: evidence, knowledge gaps, and future research. BioScience 71 (5), 531–542. https://doi.org/10.1093/biosci/biaa169.

BaileyB.G., M.R. Saunders, and Z.E. Lowe. A Cost Comparison of Five Midstory Removal Methods. In Proceedings of the 17th Biennial Southern Silvicultural Research Conference, edited by A. G. Holley, K. F. Connor, and J. D. Haywood. 535–43. e-Gen. Tech. Rep. SRS-203. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station, 2011.

Beck, Donald E. "Liriondendron Tulipifera L." In Silvics of North America: 1. Conifers; 2. Hardwoods, edited by Russell M. Burns and Barbara H. Honkala, 2:877. Agriculture Handbook 654. Washington, DC: U.S. Department of Agriculture, Forest Service, 1990.

Beck, Donald E., Della-Bianca, Lino, 1981. Yellow-poplar: characteristics and management. Agriculture Handbook. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC. September 1981.

Brooks, Mollie, Kasper Kristensen, E., Koen, J., Arni Magnusson, van Benthem, Casper, W., Berg, Anders Nielsen, Hans, J., Skaug, Martin Maechler, Benjamin, M., Bolker, 2017. glmmTMB balances speed and flexibility among packages for zeroinflated genearlized linear mixed modeling. R. J. 9 (2), 378–400. https://doi.org/10.32614/RJ-2017-066.

Brose, Patrick H., 2008. Root development of acorn-origin oak seedlings in shelterwood stands on the appalachian plateau of northern Pennsylvania: 4-year results. For. Ecol. Manag. 255, 3374–3381.

Brose, Patrick H., Rebbeck, Joanne, 2017. A comparison of the survival and development of the seedlings of four upland oak species grown in four different understory light environments. J. For. 115 (3), 159–166. https://doi.org/10.5849/jof.15-155.

Brose, Patrick H., Kurt, W.Gottschalk, Horsley, Stephen B., Knopp, Peter D., Kochenderfer, James N., McGuinness, Barbara J., Miller, Gary W., Ristau, Todd E., Stoleson, Scott H., Stout, Susan L., 2008. Prescribing regeneration treatments for mixed-oak forests in the mid-Atlantic Region. Gen. Tech. Rep. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA. August.

Craig, Jared M., Lhotka, John M., Stringer, Jeffrey W., December 2014. Evaluating initial responses of natural and underplanted oak reproduction and a shade-tolerant competitor to midstory removal. For. Sci. 60 (6), 1164–1171. https://doi.org/10.5849/forsci.13-602.

Daley, Michael J., Phillips, Nathan G., Pettijohn, Cory, Hadley, Julian L., 2007. Water Use by Eastern Hemlock (Tsuga canadensis) and Black Birch (Betula lenta): implications of effects of the Hemlock Wooly Adelgid. Can. J. For. Res. 37, 2031–2040.

Dey, Daniel C., Gary W. Miller, and John M. Kabrick "Sustaining Northern Red Oak Forests: Managing Oak from Regeneration to Canopy Dominance in Mature Stands." In: Deal, R. L., tech. ed. Integrated Restoration of Forested Ecosystems to Achieve Multiresource Benefits: proceedings of the 2007 national silviculture workshop 2007 May 7-10; Ketchikan, AK: Gen. Tech. Rep. PNW-733. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 91-105, 2008.

Evans, A., Hartman, Hamilton, Romine, R., 2018. Forest fire seasons; prohibited and permissible fires; burning permits and fees; fire control measures; criminal and civil penalties. Pub. L. No. House Bill. 4394 http://www.legis.state.wv.us/Bill_Text_HTML/2018_SESSIONS/RS/Bills/HB4394%20SUB.htm.

Fei, S., Kong, N., Steiner, K.C., Moser, W.K., Steiner, E.B., 2011. Change in Oak abundance in the Eastern United States from 1980 to 2008. For. Ecol. Manag. 262, 1370–1377.

Fei, Songlin, Gould Peter, J., Kim, C., Steiner, James, Finley, C., Marc, E., McDill, 2005. Forest regeneration composition and development in upland, Mixed-Oak forests. Tree Physiol. 25, 1495–1500.

Frankel, Susan J., Jennifer Juzwik, and David M. Rizzo. Forests (Oaks) in North America. In Global Plant Health Assessment, edited by Savary, S., et al., 152–58. International Society for Plant Pathology, 2022.

Gingrich, S.F., 1967. Measuring and evaluating stocking and stand density in upland Hardwood forests in the Central States. For. Sci. 13, 38–53.

Gottschalk, Kurt W. "Effects of Shading on Growth and Development of Northern Red Oak, Black Oak, Black Cherry, and Red Maple Seedlings. I. Height, Diameter, and Root/Shoot Ratio." In Proceedings Central Hardwood Forest Conference V, edited by J. O. Dawson and K. A. Majerus, SAF Publ. 85-05:189–195. Urbana, IL: Champaign-Urbana, IL: University of Illinois, 1985.

Hix, D.M., Lorimer, C.G., 1991. Early Stand Development on Former Oak Sites in Southwestern Wisconsin. For. Ecol. Manag. 42, 169–193.

Huffman, Thad S. Kell v. Appalachian Power Co.: Aerial Application of Herbicides on Utility Right-of-Ways. W. Va. L. Rev. West Virginia University College of Law, 1983. ⟨https://researchrepository.wvu.edu/wvlr/vol85/iss5/10⟩.

Iverson, L.R., Todd, F.H., Peters, M.P., Yaussy, D.A., 2017. Long-term response of Oak-Hickory regeneration to partial harvest and repeated fires: influence of light and moisture. Ecosphere 8 (1). https://doi.org/10.1002/ecs2.1642.

Johnson, Paul, Stephen, S., Shifley, R., Robert Rogers, 2002. The Ecology and Silviculture of Oaks. CABI Publishing, Cambridge, MA.

Lamson, Neil I.. "Betula lenta L." In Silvics of North America: 1. Conifers; 2. Hardwoods, edited by Russell M. Burns and Barbara H. Honkala, 2:877. Agriculture Handbook 654. Washington, DC: U.S. Department of Agriculture, Forest Service, 1990.

Lenth, Russell V. "Emmeans: Estimated Marginal Means, Aka Least-Squares Means." R package version 1.10.4.900001, ⟨https://rvlenth.github.io/emmeans/⟩, 2024. ⟨https://rvlenth.github.io/emmeans/⟩.

Loftis, David L., 1990b. Predicting post-harvest performance of advance red oak reproduction in the southern Appalachians. For. Sci. 36 (4), 908–916.

Loftis, David L., 1990a. A Shelterwood method for regenerating red oak in the Southern Appalachians. For. Sci. 36 (4), 917–929.

Loftis, David L., Upland oak regeneration and management. In Upland Oak Ecology Symposium: History, Current Conditions, and Sustainability. 311 p., edited by Martin A. Spetich. Gen. Tech. Rep. SRS-73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 2004.

Marquis, David A. Controlling light in small clearcuttings. Res. Pap. NE-39 Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, 1965.

Marquis, David A., 1990. Prunus serotina Ehrh. Agriculture Handbook 654. In: Russell, M., Burns, Barbara, Honkala, H. (Eds.), Silvics of North America: 1. Conifers; 2. Hardwoods, 2. U.S. Department of Agriculture, Forest Service, Washington, DC, p. 877.

McWilliams, William H., Renee A. O'Brien, Gordon C. Reese, and Karen L. Waddell. Distribution and abundance of oaks in North America. In Oak Forest Ecosystems: Ecology and Management for Wildlife, edited by William J. McShea and William M. Healy, 13–33. Baltimore, Maryland: The Johns Hopkins University Press, 2002.

METER Group, Inc. ACCUPAR LP-80 Canopy Interception and Leaf Area Index. San Francisco, CA, 2024.

Miller, Gary W., James N.Kochenderfer, and Kurt W. Gottschalk. Effect of pre-harvest shade control and fencing on Northern Red Oak seedling development in the Central Appalachians. Gen. Tech. Rep. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station, 2004.

Miller, Gary W., Brose, Patrick H., Gottschalk, Kurt W., May 2017. Advanced Oak seedling development as influenced by Shelterwood treatments, competition control, deer fencing, and prescribed fire. J. For. 115 (3), 179–189. https://doi.org/10.5849/jof.16-002.

Nowacki, G.J., Abrams, M.D., 1992. Community, Edaphic and historical analysis of mixed-oak forests of the Ridge and Valley Province in Central Pennsylvania. Can. J. For. Res. 22, 790–800.

Nowacki, Gregory J., Abrams, Marc D., February 2008. The demise of fire and 'Mesophication' of forests in the Eastern United States. BioScience 58 (2), 123–138.

Oliver, Chadwick Dearing. The development of Northern Red Oak (Quercus rubra L.) in mixed species, even-aged stands in central New England. Dissertation, Yale University, 1975.

Patterson, Clinton P., Hackworth, Zachary J., Lhotka, John M., Stringer, Jeffrey W., 2022. Light and regeneration patterns following silvicultural gap establishment in Quercus dominated stands of the Northern Cumberland Plateau, USA. For. Ecol. Manag. 505 (1).

R Core Team, 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria (https://www.R-project.org./).

Rathfon, R.A. Midstory Removal Methods Tested for Timely Release of Newly Established Oak Seedlings under Oak Shelterwoods. In Proceedings, 17th Central Hardwood Forest Conference; 2010 April 5-7, edited by Songlin Fei, John M. Lhotka, Jeffrey W. Stringer, Kurt W. Gottschalk, and Gary W. Miller, 521–34. Lexington, KY; Gen. Tech. Rep. NRS-P-78. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station, 2011.

Rebbeck, Joanne, Gottschalk, Kurt, Scherzer, Amy, 2011. Do Chestnut, Northern Red, and white oak germinant seedlings respond similarly to light treatments? Growth and biomass. Can. J. For. Res. 41, 2219–2230. https://doi.org/10.1139/X11-124.

Sander, Ivan L., Paul, S.Johnson, Watt, Richard F., 1976. A Guide for Evaluating the Adequacy of Oak Advance Reproduction. Gen. Tech. Rep. U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Schnur, G.L. "Yield, Stand, and Volume Tables for Even-Aged Upland Oak Forests." Tech. Bull. Washington, DC: U.S. Department of Agriculture, Forest Service, Allegheny Forest Experiment Station, 1937.

Schuler, Jamie L., Michael Boyce, and Gary W. Miller The Impact of Strip Clearcutting on Red Oak Seedling Development. In Proceedings of the 20th Central Hardwood Forest Conference, edited by John M. Kabrick, Daniel C. Dey, Benjamin O. Knapp, David R. Larsen, Stephen R. Shifley, and Henry E. Stelzer, 19–26. 2016 March 28-April 1; Columbia, MO. Gen. Tech. Rep. NRS-P-167. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station, 2017.

Soil Survey Staff, 2024. Natural resources conservation service, United States Department of Agriculture. Available online at the following link: http://websoilsurvey.sc.egov.usda.gov/. Accessed [06/24 Web Soil Surv. /.

Turnbull, Matthew H., Whitehead, David, Tissue, David T., Schuster, William S.F., Brown, Kim J., Engel, Victor C., Griffin, Kevin L., 2002. Photosynthetic characteristics in Canopies of Quercus rubra, Quercus Prinus and Acer rubrum differ in response to soil water availability. Oecologia 130, 515–524.

U.S. Geological Survey, 2016. National Agriculture Imagery Program. https://wvgis.wvu.edu/data/dataset.php?ID= 469.. https://wvgis.wvu.edu/data/dataset.php?ID= 469.

Vivin, P., Aussenac, G., Levy, G., 1993. Differences in drought resistance among 3 Deciduous Oak species grown in large boxes. Ann. For. Sci. 50 (3), 221–233. https://doi.org/10.1051/forest:19930301.

Widmann, Richard H., Gregory, W.Cook, Barnett, Charles J., Butler, Brett J., Griffith, Douglas M., Hatfield, Mark A., Kurtz, Cassandra M., et al., 2011. West Virginia's Forests 2008." Resour. Bull. NRS-61. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, p. 64. DVD included.