Journal of Forestry, 2019, 1–8
doi:10.1093/jofore/fvz041
Brief communication - silviculture
Received January 18, 2019; Accepted June 10, 2019
Advance Access publication July 3, 2019

Brief communication - silviculture

Can Clearcutting Reset Successional Trajectories in Upland Oak–Hickory Forests? A Case Study from Mid-Missouri

Benjamin O. Knapp, Samantha E. Anderson, Patrick J. Curtin, Casey Ghilardi, and Robert G. Rives

Benjamin O. Knapp (knappb@missouri.edu), Samantha E. Anderson (sea9c2@missouri.edu), Patrick J. Curtin (pjc535@missouri.edu), Casey Ghilardi (crgxcf@missouri.edu), Robert G. Rives (rgrytc@missouri.edu), School of Natural Resources, University of Missouri, Columbia, MO 65211.

Abstract

Securing oak regeneration is a common management challenge in the central and eastern United States. We quantified the abundance of tree species groups in clearcuts in mid-Missouri more than 30 years following harvest to determine differences in species dominance based on aspect (exposed, protected, or ridge sites). Each tree was classified as "dominant" or "suppressed" based on its relative contribution to cumulative stand stocking, following concepts of the tree–area relation. Although maples or understory species were the most abundant across all sites, oaks and hickories contributed to more than 60 percent of the dominant stems on the exposed sites. In contrast, oaks and hickories made up less than 25 percent of the dominant stems on protected and ridge sites. Results indicate that clearcutting reset the successional trajectory, from a transition to maple dominance to maintaining oak–hickory dominance, on exposed sites but not on ridge or protected sites.

Keywords: Central Hardwood Forest Region; clearcut; Gingrich stocking; oak regeneration; stem exclusion

Throughout the central and eastern United States, upland oak (*Quercus* spp.) forests have demonstrated recent patterns of successional change to non-oak species, often with replacement by species associated with more mesic conditions, such as maples (*Acer* spp.) or tulip-poplar (*Liriodendron tulipifera* L.) (Fei et al. 2011, Knott et al. 2019). The transition is commonly attributed to fire exclusion and suppression practices of the 1900s, with additional contributing factors including changes in climate patterns, loss of foundational species such as American chestnut (*Castanea dentata* [Marshall] Borkh.), and increasing pressure from herbivory or invasive competitors (Nowacki and Abrams 2008, McEwan et al. 2011, Webster et al. 2018). As much of the forestland in the region is aging synchronously (Shifley et al. 2014), canopy tree mortality because of recent forest health issues or stand maturity, coupled with low potential for oak-regeneration success because of a lack of advance reproduction, creates conditions for accelerated successional change across the landscape.

Challenges with oak regeneration have been recognized for decades (Loftis and McGee 1993), and a large body of research has informed silvicultural practices for oak-regeneration success. As seedlings, upland oaks prioritize growth to the root system rather than the shoot and therefore may be outcompeted by faster-growing species (Larsen and Johnson 1998). However, the development of relatively large root systems and the ability to resprout from the root collar contribute to persistence of oak regeneration within the forest understory (Johnson et al. 2009). The accumulation of oak advance reproduction prior to canopy release is often critical to regeneration success,

Downloaded from https://academic.oup.com/jof/advance-article-abstract/doi/10.1093/jofore/fvz041/5527930 by University of Missouri-Columbia user on 08 July 2019

Copyright © 2019 Society of American Foresters

Management and Policy Implications

Legacies of past land use and contemporary forest-management practices together contribute to the patterns of forest succession observed across the modern landscape. In the central and eastern United States, one commonly observed pattern is the transition of oak–hickory forests to dominance of more mesic species such as maples. A large body of research has informed our understanding of oak regeneration ecology, yet achieving widespread oak regeneration success has remained a challenge on an operational scale. In this study, we quantified the abundance of common species groups, including oaks, hickories, and maples, after more than three decades following clearcutting on different site types in mid-Missouri, using a new method to classify trees as "dominant" or "suppressed." Clearcutting on relatively dry, exposed slopes resulted in dominance of oak–hickory in the developing stand, whereas clearcutting on more mesic, protected slopes resulted in dominance of maples and other species. These results support that oak regeneration success following clearcutting is more likely on lower-quality sites. Thus, this work supports the need for (1) active forest management to reset successional trajectories of upland oak forests and (2) application of site-specific silvicultural prescriptions, based on regeneration ecology of upland oaks, to reach desired forest management objectives.

although sprouting of harvested trees can also contribute to the new regeneration cohort (Sander et al. 1984, Brose et al. 2008, Steiner et al. 2008). In many oak-dominated forests, the lack of oak advance reproduction is associated with increased abundance of more shade-tolerant and often fire-sensitive species (Abrams 1992, Arthur et al. 2012, Brose et al. 2014). The development of oak advance reproduction varies with site quality, with greater abundance commonly observed on lower-quality sites (Kabrick et al. 2014, Iverson et al. 2018).

Upland oak forests of Missouri, located near the western border of the Central Hardwood Forest Region, generally experience fewer oak-regeneration issues than locations further east, in part because of lower site productivity and fewer competing species. Several studies have demonstrated oak-regeneration success using either even-aged or uneven-aged silvicultural systems in the Missouri Ozarks (Kabrick et al. 2008, Fan et al. 2015, Olson et al. 2017). As opposed to regeneration methods with partial canopy retention, which tend to favor white oak species because of their greater shade tolerance, clearcutting has been reported to favor both red oak and white oak species groups (Kabrick et al. 2008, Fan et al. 2015). The relatively xeric conditions and lack of competitors such as tulip-poplar increase the success of oak regeneration following clearcutting in this region.

Despite the apparent edaphic suitability of much of Missouri for oak-dominated forests, recent studies have documented increases in mesic competitors throughout the state (Olson et al. 2017, Knapp and Pallardy 2018). In particular, portions of mid-Missouri that have soils with high pH and water-holding capacity support abundant sugar maple (*Acer saccharum* Marshall) within the forest midstory (Nigh et al. 1985). A network of long-term forest monitoring plots in mid-Missouri has documented continual increase in sugar maple since the 1960s in the absence of forest management (Rochow 1972, Pallardy et al. 1988, Belden and Pallardy 2009, Knapp and Pallardy 2018). Located near these long-term monitoring plots, several small (3–10-acre) clearcuts (i.e., complete overstory removal harvests) were established across a range of site conditions in the 1980s. In 2016, we sampled these clearcuts to improve our understanding of the effects of clearcutting on forest composition after several decades of stand development.

Given that the stem exclusion stage of stand development following clearcutting is a period of height differentiation and abundant mortality of suppressed stems, evaluating the population of dominant stems is important when assessing patterns of stand development (Peet and Christensen 1987, Vickers et al. 2014). The objectives of this study were: (1) to separate the population of trees likely to persist through stand development to make up the future canopy (referred to as dominant trees) from those likely to remain in the midstory or die (referred to as suppressed trees) decades following clearcutting and (2) to evaluate effects of aspect on forest composition for the full regeneration cohort, the population of dominant trees, and the population of suppressed trees.

Methods

Study Site

The study was located in the University of Missouri's Baskett Wildlife Research and Education Center (BWREC, formerly Ashland Wildlife Area) in Boone

Downloaded from https://academic.oup.com/jof/advance-article-abstract/doi/10.1093/jofore/fvz041/5527930 by University of Missouri-Columbia user on 08 July 2019

County, MO (38°45′44″N, 92°11′40″W). The BWREC is located within the Outer Ozark Border Subsection of the Ozark Highlands Ecological Section (Nigh and Schroeder 2002). The climate of the region is warm, humid, and continental, with a mean maximum monthly temperature of 88.2° F in July, mean minimum monthly temperature of 19.8° F in January, and mean annual precipitation of 40.1 in. from 1970 through 2016 (National Climatic Data Center, Columbia Regional Airport Station).

The clearcuts were established across a range of site conditions in the 1980s (Table 1). Two clearcuts were established in each of three aspect classes, hereafter referred to as "exposed," "protected," and "ridge." The exposed clearcuts were located on west-facing slopes (mean 14.7 percent slope), and the protected clearcuts were located on north-facing slopes (mean 19.1 percent slope). The ridge clearcuts had slope <6 percent (Table 1). Although pretreatment data do not exist, the adjacent long-term monitoring plots suggest that the stands were mature, oak-dominated forests prior to the clearcut harvests, with composition varying with site quality (see Knapp and Pallardy 2018). Forests in the area were mostly second-growth, with a history of open grazing during the period of early settlement but no harvest activity following the 1930s. Soils were Alfisols that were formed in residuum of dolomite or limestone (Bardley–Clinkenbeard, Rocheport soils series), glacial till (Winnegan soil series), or loess (Marion soil series), each of which supports hardwood forests or woodlands (Web Soil Survey, accessed December 19, 2018).

Data Collection

Within each clearcut, we established several 0.05-acre circular sampling plots (26.3-ft radius). Plot locations were determined using a randomized systematic approach within a Geographic Information Systems (GIS) framework. Within each clearcut, sampling plots were located along one or two transects oriented parallel to the topographic gradient, such that sampling occurred across a range of slope positions. In the exposed and protected clearcuts, we established two sampling transects at random starting-points, with at least 75 ft between each transect; within the ridge clearcuts, one sampling transect was used per clearcut. Within GIS, we determined that the change in elevation along the slopes of the exposed and protected clearcuts was approximately 80–100 ft. Three sampling plots were randomly located along each transect to maintain at least a 20-ft change in elevation and at least a 75-ft distance between each plot. Within each plot, all woody stems of ≥1.5 in. diameter at breast height (dbh) were identified by species, and the dbh of each was recorded.

Data Analysis

We used a simple method, based on the principles of Gingrich stocking (Gingrich 1967), to separate the population of dominant trees from the suppressed trees for each plot. The concept of Gingrich stocking considers the allocation of growing space to the trees within a given stand, with the growing space used by a single tree dependent on tree-size (diameter):

$$S_i = -0.00507 + 0.01698D + 0.00317D^2 \tag{1}$$

where S_i = stocking percent for individual tree i, and D = diameter at breast height (in.). Stand-level stocking is expressed as the percentage of the normal condition for maximum stocking of undisturbed upland hardwood stands (Gingrich 1967). Importantly, the method also defines crown closure (Krajicek et al. 1961), or the "B-line" on the stocking chart, as the point at which competition for growing space begins (i.e., all freely available growing space is occupied by existing trees). The B-line on the stocking chart ranges from around 57 to 59 percent stocking, depending on quadratic mean of tree size.

Table 1. Summary of descriptive characteristics of clearcuts included in the study.

Clearcut	Date	Size (acres)	Azimuth	Aspect	Slope (percent)	Soil series	Elevation range (ft)	Site index
1	1983	3.9	255	Exposed	16.9	Bardley–Clinkenbeard complex	680–780	66
2	1983	7.9	260	Exposed	12.6	Winnegan	690–760	68
3	1983	3.6	355	Protected	20.1	Winnegan	660–720	69
4	1983	9.5	10	Protected	18.1	Rocheport–Bonnefemme complex	650–730	70
5	1988	3.3	30	Ridge	5.5	Marion	758–780	67
6	1988	4.1	75	Ridge	4.4	Marion	759–794	66

Note: Site index is for white oak, base age 50.

Downloaded from https://academic.oup.com/jof/advance-article-abstract/doi/10.1093/jofore/fvz041/5527930 by University of Missouri-Columbia user on 08 July 2019

To determine dominant trees within the developing clearcuts, we assumed that individual trees that occupied more growing space were more competitive than their neighbors. Following the concept of Gingrich stocking, we assumed that freely available growing space within the stand was occupied at >60 percent stand stocking. We calculated the percentage stocking contribution of each tree based on Equation 1 and then ranked the tree list of each plot by individual tree-stocking contribution (greatest to least). Using the ranked tree list, we calculated the stand-level stocking (cumulative stocking) for all trees within the plot to create a cumulative distribution function of stand-level stocking (Figure 1A). At 60 percent stocking on the cumulative distribution function, we assumed that freely available growing space was fully occupied by the most competitive trees on the site (i.e., the dominant trees), with the additional contribution to stand-level stocking occupied by suppressed trees. The cumulative distribution function for stand stocking was then expressed in relation to tree diameter rather than tree rank (Figure 1B).

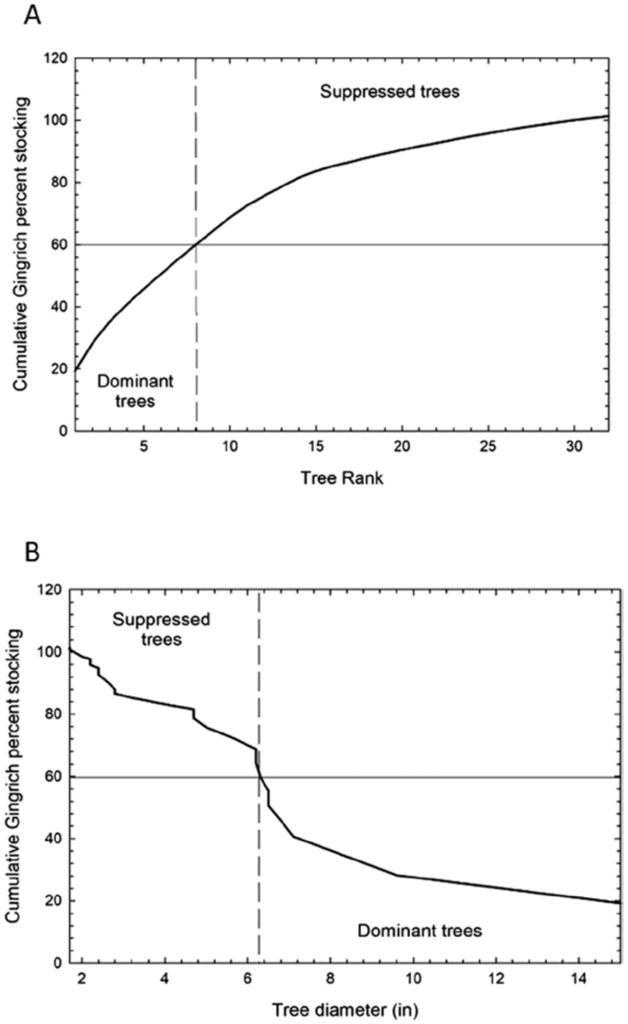

Figure 1. Conceptual illustration of separation of dominant and suppressed trees based on cumulative distribution of Gingrich stocking for a randomly selected sampling plot (0.05 acre). The cumulative distribution based on tree rank of stocking contribution (A) is converted to tree diameter (B). At 60 percent cumulative percent stocking, the stand is assumed to have all freely available growing space occupied by the most competitive trees, with the resulting populations of "dominant" and "suppressed" trees shown on the figures.

We evaluated the abundance of stems for the following species groups: eastern redcedar (*Juniperus virginiana* L.), hickories (*Carya cordiformis* [Wangenh.] K. Koch, *C. glabra* [Mill.] Sweet, *C. ovata* [Mill.] K. Koch, *C. tomentosa* [Lam.] Nutt.), maples (*Acer saccharum* Marshall; *A. rubrum* L.), red oaks (*Quercus rubra* L., *Q. velutina* Lam.), white oaks (*Q. alba* L., *Q. muehlenbergii* Engelm.), "other" overstory species (e.g., *Fraxinus americana* L., *F. pennsylvanica* Marshall, *Juglans nigra* L., *Prunus serotina* Ehrh., *Sassafras albidum* [Nutt.] Nees), and understory species (*Carpinus caroliniana* Walter, *Cornus florida* L., *Ostrya virginiana* [Mill.] K. Koch). We determined the proportional contribution of each species group to stand stocking across the diameter distribution. For each sampling plot, we determined the stem density (number of trees per acre) and the relative stem density for each species group for the dominant population, the suppressed population, and all trees present. Mean values were calculated for each clearcut, and we used mixed linear models to determine differences in stem density and relative stem density among sites (exposed, ridge, and protected aspects) for each species group, with the experimental unit (i.e., the clearcut) included as a random effect in the model. In the event of significant effects of aspect, pairwise comparisons were made using the Tukey Honestly Significant Difference adjustment. Analyses were conducted using SAS software (SAS 9.4, SAS Institute, Cary, NC).

Results

Total stand stocking was 94 percent, 85 percent, and 93 percent for the exposed, ridge, and protected clearcuts, respectively. The exposed clearcuts averaged 81.9 ft^2 per acre basal area and 774 trees per acre, and had a quadratic mean diameter of 4.4 in.; ridge clearcuts averaged 73.1 ft^2 per acre basal area and 789 trees per acre, and had a quadratic mean diameter of 4.1 in.; and the protected clearcuts averaged 73.6 ft^2 per acre basal area and 986 trees per acre, and had a quadratic

Downloaded from https://academic.oup.com/jof/advance-article-abstract/doi/10.1093/jofore/fvz041/5527930 by University of Missouri-Columbia user on 08 July 2019

mean diameter of 3.7 in. The dbh at which the dominant and suppressed populations differentiated (i.e., the point of cumulative stocking of 60 percent) varied slightly among the aspects, at 4.4 in. for the exposed clearcuts, 3.4 in. for the ridge clearcuts, and 3.5 in. for the protected clearcuts (Figure 2).

Based on all the stems present, maples made up the most abundant species group on the exposed and ridge clearcuts, and the understory species group was the most abundant on the protected clearcuts (Table 2). Stem density of understory species was significantly greater on the protected sites than on the exposed sites (*P* = .013) and the ridge sites (*P* = .014). For the population of dominant stems, the red oak group was in significantly greater abundance on the exposed sites than on the protected sites (*P* = .040). There were no significant differences in red oak stem density between the ridge sites and the exposed (*P* = .070) or protected (*P* = .670) sites (Table 2). The population of suppressed stems was dominated by maples on the exposed and ridge sites and by understory species on the protected sites (Table 2). On the exposed sites, the red oak, white oak, and hickory groups combined to contribute 60 percent of the dominant stems but only 20 percent of the suppressed stems (Figure 3). In contrast, maples made up 25 percent of the dominant stems and over 50 percent of the suppressed stems. On the protected and ridge sites, the red oak, white oak, and hickory groups made up less than 25 percent of the dominant stems.

Discussion

Stand development following clearcutting is a dynamic process in which an initial large population of small trees is greatly reduced through growth, differentiation, and mortality over time (Oliver 1980, Peet and Christensen 1987). Given that the majority of the stems present during the early stages of stand development will not persist to contribute to the future overstory, evaluating species composition based on the total population may be misleading. The method we used is predicated on the concept of the tree–area relation (Chisman and Schumacher 1940), with the assumption that larger trees are more competitive, and defined the threshold for dominant stature based on stand stocking. We anticipate the probability of persistence as a canopy tree to decrease as tree diameter decreases to the dominance threshold.

Our results support that the effectiveness of clearcutting for oak regeneration depends, in part, on site quality. Studies from good-quality sites of the Appalachians have reported regeneration failures of oaks following clearcutting (Beck and Hooper 1986, Brashears et al. 2004), whereas studies from relatively harsh sites of the Missouri Ozarks have demonstrated the potential for

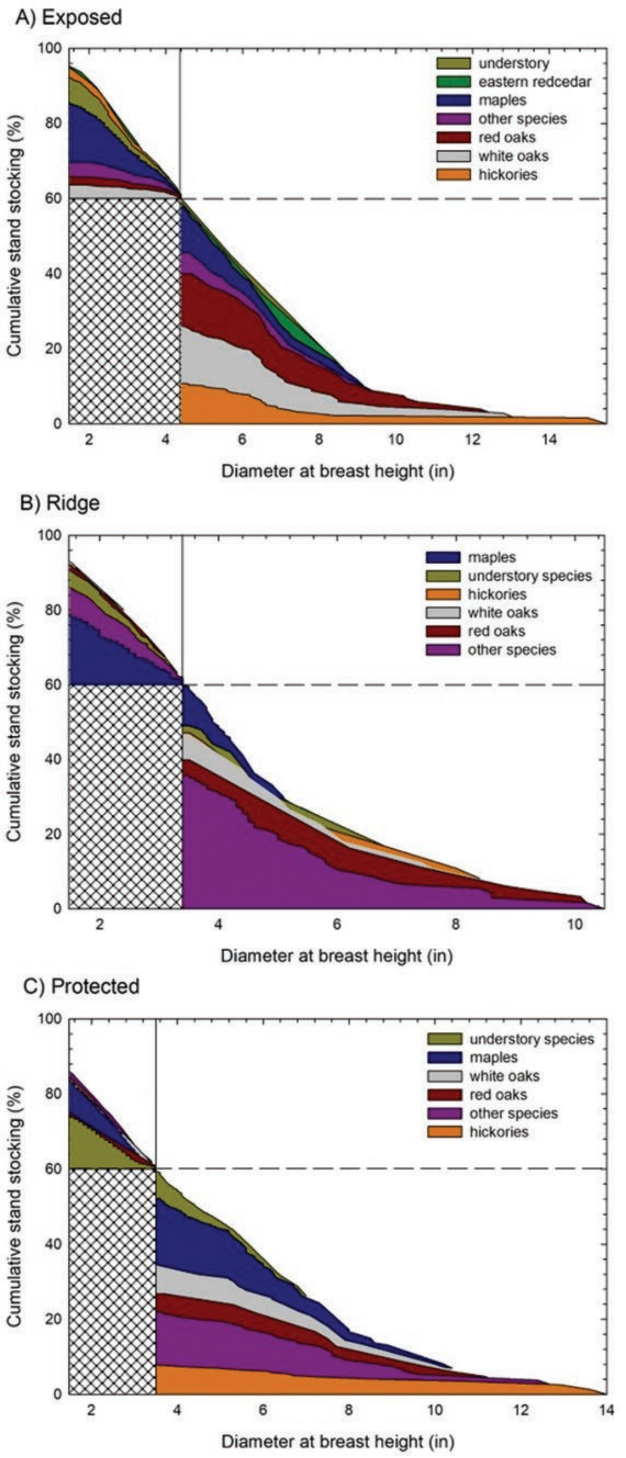

Figure 2. Cumulative stand stocking by diameter at breast height, showing contribution by species group for clearcuts on (A) exposed sites, (B) ridge sites, and (C) protected sites. The horizontal dashed line shows 60 percent stand stocking separating dominant from suppressed populations of trees, and the vertical solid line shows the corresponding diameter at that point.

Downloaded from https://academic.oup.com/jof/advance-article-abstract/doi/10.1093/jofore/fvz041/5527930 by University of Missouri-Columbia user on 08 July 2019

Table 2. Stem density (number of trees per acre) by species group and aspect class for dominant stems, suppressed stems, and all stems.

	Aspect						
	Exposed		Ridge		Protected		
	Mean	SE	Mean	SE	Mean	SE	*P*-value
Dominant stems							
Eastern redcedar	3.3	0.0	3.3	3.3	1.7	1.7	.829
Hickories	36.6	23.3	6.7	0.0	23.3	13.3	.483
Maples	74.9	21.7	179.9	93.3	106.6	13.3	.485
Other	28.3	5.0	133.2	53.3	51.6	1.7	.182
Red oaks	56.6^{a}	6.7	23.3^{ab}	3.3	15.0^{b}	8.3	.039
Understory	10.0	0.0	43.3	30.0	81.6	18.3	.185
White oaks	50.0	20.0	30.0	16.7	20.0	20.0	.583
Suppressed stems							
Eastern redcedar	8.3	5.0	0.0	0.0	0.0	0.0	.208
Hickories	45.0	11.7	10.0	10.0	15.0	15.0	.245
Maples	248.1	28.3	293.1	13.3	164.9	38.3	.106
Other	41.6	25.0	159.9	119.9	28.3	11.7	.454
Red oaks	21.7	1.7	16.7	16.7	6.7	0.0	.594
Understory	104.9	15.0	79.9	13.3	258.1	51.6	.053
White oaks	45.0	5.0	6.7	0.0	23.3	23.3	.287
All stems							
Eastern redcedar	11.7	5.0	3.3	3.3	1.7	1.7	.257
Hickories	81.6	35.0	16.7	10.0	40.0	3.3	.235
Maples	323.1	50.0	473.0	106.6	271.5	51.6	.282
Other	69.9	20.0	293.1	173.2	79.9	10.0	.343
Red oaks	78.3	8.3	40.0	20.0	21.7	8.3	.120
Understory	114.9^{b}	15.0	123.2^{b}	16.7	339.7^{a}	33.3	.010
White oaks	94.9	25.0	36.6	16.7	35.0	35.0	.330

Note: P-values indicate the effect of aspect within a species group; the same superscript letter indicates no significant difference from pairwise comparisons of aspect within a species group. SE, standard error.

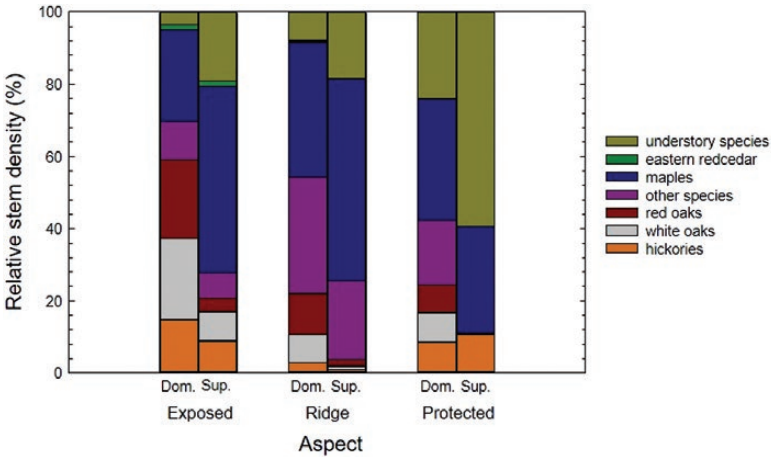

Figure 3. Relative stem density by species group for dominant (Dom.) and suppressed (Sup.) trees on each aspect.

regeneration success (Kabrick et al. 2008). In the Hoosier National Forest of southern Indiana, Swaim et al. (2018) recently documented a reduced importance value of oaks 23 years following clearcutting, with the greatest reductions on better-quality sites, and Morrissey et al. (2008) reported that the relative density of dominant

Downloaded from https://academic.oup.com/jof/advance-article-abstract/doi/10.1093/jofore/fvz041/5527930 by University of Missouri-Columbia user on 08 July 2019

or codominant oaks in 21–35-year-old clearcuts was greatest on upper slope positions of xeric, exposed sites. Similarly, clearcutting during the 1980s and 1990s on the Shawnee National Forest in Illinois resulted in stands with the most competitive oaks on upper slope positions and south- or west-facing aspects up to 26 years after harvest (Groninger and Long 2008). Our results indicate that clearcutting resulted in stands developing toward oak–hickory forests on exposed sites but not on the ridge or protected sites at BWREC.

We did not expect the low abundance of oak stems on the ridge clearcuts, which instead were dominated by sugar maple and species such as ashes, sassafras, and black cherry. Because of a lack of pretreatment data from the clearcut areas, it is unclear if there were any differences in advance reproduction between the exposed and ridge sites. However, the sapling layer from the long-term monitoring plots was generally dominated by sugar maple rather than oaks in 1982 (Knapp and Pallardy 2018), suggesting that advance reproduction was not well developed on either exposed or ridge sites. Observations indicate that stump sprouting was an important contributor to oak regeneration on the exposed clearcuts and that poor stump sprouting on the ridge clearcuts likely contributed to the lack of oak dominance on those sites. In addition, differences in soil type between the exposed and ridge sites, including greater water-holding capacity and a loess cap on the ridge sites, may have accentuated the observed compositional differences. However, it has yet to be seen if species associated with more mesic conditions will persist as canopy trees on the ridge sites given the inherently dry conditions and periodic drought events within the region.

The widespread successional shifts away from oak in upland forests of the central and eastern United States have been attributed to several factors, notably changes in disturbance patterns (Nowacki and Abrams 2008, Fei et al. 2011, McEwan et al. 2011, Knott et al. 2019). In the absence of forest management, shade-tolerant species have accumulated in small-diameter classes at BWREC, with the greatest magnitude of change on relatively mesic sites that are well suited for sugar maple (Nigh et al. 1985, Knapp and Pallardy 2018). This study demonstrates alternative outcomes following clearcutting in mid-Missouri, including the potential to regenerate oak-dominated stands on dry, exposed sites and the potential for oak-regeneration challenges without additional silvicultural intervention on protected sites and ridges. More broadly, this work supports the need for (1) active forest management if landowners intend to reset successional trajectories of upland oak forests and (2) application of site-specific silvicultural prescriptions, based on regeneration ecology of upland oaks, to reach the desired forest-management objectives.

Acknowledgments

We are grateful for the efforts of Frank Thompson during the establishment of the clearcuts, as well as for the field and technical support provided by Bennett Wickenhauser. This project was supported by funding from the National Institute of Food and Agriculture, US Department of Agriculture, McIntire-Stennis Capacity Grant project 233870.

Literature Cited

Abrams, M.D. 1992. Fire and the development of oak forests. *Bioscience* 42(5):346–353.

Arthur, M.A., H.D. Alexander, D.C. Dey, C.J. Schweitzer, and D.L. Loftis. 2012. Refining the oak-fire hypothesis for management of oak-dominated forests of the eastern United States. *J. For.* 110(5):257–266.

Beck, D.E., and R.M. Hooper. 1986. Development of a southern Appalachian hardwood stand after clearcutting. *South. J. Appl. For.* 10(3):168–172.

Belden, A.C., and S.G. Pallardy. 2009. Successional trends and apparent *Acer saccharum* regeneration failure in an oak–hickory forest in central Missouri, USA. *Plant Ecol.* 204(2):305–322.

Brashears, M.B., M.A. Fajvan, and T.M. Schuler. 2004. An assessment of canopy stratification and tree species diversity following clearcutting in Central Appalachian Hardwoods. *For. Sci.* 50(1):54–64.

Brose, P.H. 2014. Development of prescribed fire as a silvicultural tool for the upland oak forests of the eastern United States. *J. For.* 112(5):525–533.

Brose, P.H., K.W. Gottschalk, S.B. Horsley, P.D. Knopp, J.N. Kochenderfer, B.J. McGuinness, G.W. Miller, T.E. Ristau, S.H. Stoleson, and S.L. Stout. 2008. *Prescribing regeneration treatments for mixed-oak forests in the mid-Atlantic region*. USDA Forest Service Gen. Tech. Rep. GTR-NRS-33, Northern Research Station, Newtown Square, PA. 100 p.

Chisman, H.H., and F.X. Schumacher. 1940. On the tree–area ratio and certain of its applications. *J. For.* 38(4):311–317.

Fan, Z., Q. Yao, D. Dey, M. Spetich, A. Ezell, S. Shifley, J. Kabrick, and R. Jensen. 2015. Efficacy and associated factors of even- and uneven-aged management to promote oak regeneration in the Missouri Ozarks. *For. Sci.* 61(2):397–408.

Fei, S., N. Kong, K.C. Steiner, W.K. Moser, and E.B. Steiner. 2011. Change in oak abundance in the eastern United States from 1980 to 2008. *Forest Ecol. Manag.* 262(8):1370–1377.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. *For. Sci.* 13(1):38–53.

Downloaded from https://academic.oup.com/jof/advance-article-abstract/doi/10.1093/jofore/fvz041/5527930 by University of Missouri-Columbia user on 08 July 2019

Groninger, J.W., and M.A. Long. 2008. Oak ecosystem management considerations for Central Hardwoods stands arising from silvicultural clearcutting. *North. J. Appl. For.* 25(4):173–179.

Iverson, L.R., M.P. Peters, J.L. Bartig, J. Rebbeck, T.F. Hutchinson, S.N. Matthews, and S. Stout. 2018. Spatial modeling and inventories for prioritizing investment into oak–hickory restoration. *Forest Ecol. Manag.* 424:355–366.

Johnson, P.S., S.R. Shifley, and R. Rogers. 2009. *The ecology and silviculture of oaks*. 2nd ed. CAB International, Cambridge, MA. 580 p.

Kabrick, J.M., J.L. Villwock, D.C. Dey, T.L. Keyser, and D.R. Larsen. 2014. Modeling and mapping oak advance reproduction density using soil and site variables. *For. Sci.* 60(6):1107–1117.

Kabrick, J.M., E.K. Zenner, D.C. Dey, D. Gwaze, and R.G. Jensen. 2008. Using ecological land types to examine landscape-scale oak regeneration dynamics. *Forest Ecol. Manag.* 255(7):3051–3062.

Knapp, B.O., and S.G. Pallardy. 2018. Forty-eight years of forest succession: Tree species change across four forest types in mid-Missouri. *Forests* 9(10):633.

Knott, J.A., J.M. Desprez, C.M. Oswalt, and S. Fei. 2019. Shifts in forest composition in the eastern United States. *Forest Ecol. Manag.* 433:176–183.

Krajicek, J.E., K.A. Brinkman, and S.F. Gingrich. 1961. Crown competition—a measure of density. *For. Sci.* 7(1):35–42.

Larsen, D.R., and P.S. Johnson. 1998. Linking the ecology of natural oak regeneration to silviculture. *Forest Ecol. Manag.* 106(1):1–7.

Loftis, D.L., and C.E. McGee. 1993. *Oak regeneration: Serious problems, practical solutions*. USDA Forest Service Gen. Tech. Rep. GTR-SE-84, Southeastern Forest Experiment Station, Asheville, NC. 319 p.

McEwan, R.W., J.M. Dyer, and N. Pederson. 2011. Multiple interacting ecosystem drivers: Toward an encompassing hypothesis of oak forest dynamics across eastern North America. *Ecography* 34(2):244–256.

Morrissey, R.C., D.F. Jacobs, J.R. Seifert, B.C. Fischer, and J.A. Kershaw. 2008. Competitive success of natural oak regeneration in clearcuts during the stem exclusion stage. *Can. J. Forest Res.* 38(6):1419–1430.

Nigh, T.A., S.G. Pallardy, and H.E. Garrett. 1985. Sugar maple–environment relationships in the River Hills and Central Ozark Mountains of Missouri. *Am. Midl. Nat.* 114(2):235–251.

Nigh, T.A., and W.A. Schroeder. 2002. *Atlas of Missouri ecoregions*. Missouri Department of Conservation, Jefferson City, MO. 212 p.

Nowacki, G.J., and M.D. Abrams. 2008. The demise of fire and "mesophication" of forests in the eastern United States. *BioScience* 58(2):123–138.

Oliver, C.D. 1980. Forest development in North America following major disturbances. *Forest Ecol. Manag.* 3:153–168.

Olson, M.G., B.O. Knapp, and J.M. Kabrick. 2017. Dynamics of a temperate deciduous forest under landscape-scale management: Implications for adaptability to climate change. *Forest Ecol. Manag.* 387:73–85.

Pallardy, S.G., T.A. Nigh, and H.E. Garrett. 1988. Changes in forest composition in central Missouri: 1968–1982. *Am. Midl. Nat.* 120(2):380–390.

Peet, R.K., and N.L. Christensen. 1987. Competition and tree death. *BioScience* 37(8):586–595.

Rochow, J.J. 1972. A vegetational description of a mid-Missouri forest using gradient analysis techniques. *Am. Midl. Nat.* 87(2):377–396.

Sander, I.L., P.S. Johnson, and R. Rogers. 1984. *Evaluating oak advance reproduction in the Missouri Ozarks*. USDA Forest Service Res. Pap. RP-NC-251, North Central Forest Experiment Station, St. Paul, MN. 16 p.

Shifley, S.R., W.K. Moser, D.J. Nowak, P.D. Miles, B.J. Butler, F.X. Aguilar, R.D. DeSantis, and E.J. Greenfield. 2014. Five anthropogenic factors that will radically alter forest conditions and management needs in the northern United States. *For. Sci.* 60(5):914–925.

Steiner, K.C., J.C. Finley, P.J. Gould, S. Fei, and M. McDill. 2008. Oak regeneration guidelines for the Central Appalachians. *North. J. Appl. For.* 25(1):5–16.

Swaim, J.T., D.C. Dey, M.R. Saunders, D.R. Weigel, C.D. Thornton, J.M. Kabrick, and M.A. Jenkins. 2018. Overstory species response to clearcut harvest across environmental gradients in hardwood forests. *Forest Ecol. Manag.* 428:66–80.

Vickers, L.A., D.R. Larsen, B.O. Knapp, J.M. Kabrick, and D.C. Dey. 2014. The impact of overstory density on sapling height growth in the Missouri Ozarks: Implications for interspecific differentiation during canopy recruitment. *Can. J. Forest Res.* 44(11):1320–1330.

Webster, C.R., Y.L. Dickinson, J.I. Burton, L.E. Frelich, M.A. Jenkins, C.C. Kern, P. Raymond, M.R. Saunders, M.B. Walters, and J.L. Willis. 2018. Promoting and maintaining diversity in contemporary hardwood forests: Confronting contemporary drivers of change and the loss of ecological memory. *Forest Ecol. Manag.* 421:98–108.

Downloaded from https://academic.oup.com/jof/advance-article-abstract/doi/10.1093/jofore/fvz041/5527930 by University of Missouri-Columbia user on 08 July 2019