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silviculture

Proactive Restoration: Planning, Implementation, and Early Results of Silvicultural Strategies for Increasing Resilience against Gypsy Moth Infestation in Upland Oak Forests on the Daniel Boone National Forest, Kentucky

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Determining targets in forest restoration is a complicated task that can be facilitated by cooperative partnerships. Too often restoration plans are implemented after adverse events that cause widespread tree mortality, such as drought or insect outbreaks, have occurred. Reactive management precludes the use of preemptive management techniques that can result in more effective restoration. The potential recognition and risks associated with a large-scale mortality event cultivated a proactive partnership among managers, stakeholders, and researchers on the Daniel Boone National Forest in Kentucky. This partnership resulted in the development of innovative proactive approaches to mitigate the negative impacts of threat of declining forest health, thus reducing the need for untested and expensive postdisturbance restorative operations. The partnership comprised four Research Work Units in the USDA Forest Service (including the Northern and Southern Research Stations), three universities (one land grant and two liberal arts), two natural resource state agencies, private logging contractors, an electrical utility, and National Forest system personnel at the district, forest supervisor, and Washington office levels. We tested forest management prescriptions designed to meet targets for future forest conditions. The goal of the silviculture treatments was to improve forest health and productivity to increase resilience to and/or avoidance of exotic invasive insect defoliation and oak decline. Treatments varied from high levels of disturbance to low levels of disturbance and ranged from even-aged regeneration treatments coupled with prescribed burning to thinning. Research assessed the alteration in species composition and stand structure, the projected regeneration outcomes and the costs and operational efficacy of mechanized forest operations used to implement the treatments. The relatively large scale of the study and diversity of treatments has afforded additional multidisciplinary research activities. Via partnership building and information and technology sharing, this project has been sustained for 10 years.

Keywords: silviculture, gypsy moth, Daniel Boone National Forest, sustainability, *Quercus* spp.

The Cumberland Plateau, the southernmost section of the physiographic province of the Appalachian Plateau, comprises more than 9 million acres of forestland (Fenneman 1938, Smalley 1986). Kentucky's Daniel Boone National Forest (DBNF), London District, lies in the heart of the Cumberland Plateau. On the Plateau uplands, mixed hardwood forests dominate, and oaks are the most widespread genus, with the most common being white oak (*Quercus alba* L.), scarlet oak (*Quercus coccinea* Muench.), black oak (*Quercus veluntina* Lamarck), northern red oak (*Quercus rubra* L.), post oak (*Quercus stellata* Wang.), and chestnut oak (*Quercus montana* L.) (Braun 1950, Hinkle 1989). On the most xeric sites, oaks such as chestnut oak and scarlet oak dominate, and on less xeric sites, northern red oak and white oak are more common. These stands also contain myriad species, including hickories (*Carya* spp.), maples (*Acer* spp.), yellow-

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poplar (*Liriodendron tulipifera* L.), sourwood (*Oxydendrum arboretum* DC), sassafras (*Sassafras albidum* [Nutt.] Nees.), and scattered pine (*Pinus* spp.). Stands are considered stressed due to site conditions, management histories, competition between species, and other disturbances. Another potential stressor on Kentucky's forests is the encroachment of the European gypsy moth (*Lymantria dispar* L.).

Silviculture can be used to improve forest health while providing for a host of utilitarian and ecological values (Waring and O'Hara 2005). Application of silvicultural methods to improve forest health will require ecological and forest management expertise and will also require policies and partnerships that facilitate management implementation and forest health monitoring. Public lands offer the most applicable opportunities to use silviculture to improve forest health because of restoration and multiple-use goals.

Oak decline is a widespread and long-term forest health issue throughout the eastern hardwood forests in North America (Starkey et al. 1989, Oak et al. 1996) and in Europe (Thomas et al. 2002). Causes of oak decline include inciting factors, such as severe environmental conditions, and predisposing factors, such as tree age or competition for light (Starkey et al. 1989). Preemptive mitigation strategies for oak decline have included prescribed fire (Spetich and He 2008) and regeneration harvests or thinning of the most susceptible stands (Voelker et al. 2008). The oak-dominated forests of the Cumberland Plateau are highly susceptible to oak decline, as they are characterized by all three risk factors outlined by Manion (1981): the predisposing factors of mature trees and high tree densities; the inciting factors of changing climate and past droughts; and the contributing factor of the potential of gypsy moth defoliation

The gypsy moth currently infests 25% of its potential range in eastern North America and is spreading at a rate of 13 miles per year (Liebhold et al. 1989, 1992). A national management program was initiated in 2000 to slow the spread of gypsy moth and has reduced the spread rate by 50%. Gypsy moth is estimated to spread to the northern Cumberland Plateau over the next 15–30 years with trap catches of gypsy moth males occurring in northeastern Kentucky over the last several years. Silvicultural treatments that increased tree and crown vigor were recommended to reduce gypsy moth impacts, but extensive empirical testing of treatments has not yet been conducted (Gottschalk 1993, Gottschalk et al. 1998). Silviculture of upland oak-dominated forests is covered in detail by Johnson et al. (2009). Application of prescriptions across the physiographic region for upland oak systems has resulted in a few techniques that may be applicable to preemptive restoration, such as the situation with the southern movement of the gypsy moth. Both regeneration and intermediate stand treatments are needed to mitigate the susceptibility and vulnerability to gypsy moth and oak decline. Our strategy was to examine forest management already approved via a US Department of Agriculture (USDA) Forest Service National Forest Plan in the context of mitigating the known impacts caused by gypsy moth defoliation (Gottschalk 1993).

Recommendations to combat oak decline or gypsy moth have been largely developed through modeling of predicted mortality or age structure using existing tree-, stand-, or landscape-level data (Oak et al. 1996, Spetich and He 2008, Voelker et al. 2008), but potential silvicultural strategies have not been thoroughly tested. A variety of both regeneration and intermediate stand treatments, including prescribed fire and thinning, need to be tested for their efficacy in mitigating for the susceptibility and vulnerability to gypsy moth and oak decline. Preemptive restoration attempts to include altering stand composition and structure to reduce growth declines or mortality and is based on metrics such as tree species composition, tree vigor, and canopy position (Fajvan and Gottschalk 2012).

In this study, we examined treatments that forest managers might use to increase overall stand vigor that have been suggested for mitigation of future gypsy moth defoliation and oak decline and to regenerate stands while maintaining a high oak component (Starkey et al. 1989, Gottschalk 1993, Voelker et al. 2008). We studied various forest management treatments already approved as management options within the USDA National Forest Plan (USDA Forest Service 2004), and the treatments were also applied under the auspices of the Healthy Forest Restoration Act of 2003 (HFRA). The study was implemented to focus not only on the ecology, physical environment, and biodiversity of the ecosystem but also on the socioeconomic aspects of restoration. As a result, the study developed into a multidisciplinary research project, involving more than 50 cooperators and interest groups. We discuss strategies and challenges during planning and implementation of this study and offer recommendations for implementation of similar silvicultural research projects. We provide applicable research results on competitiveness of oak regeneration, and we also project regeneration outcomes to predict future forest conditions. Finally, we examine the costs and operational performance of an integrated mechanized forest operation used to implement the treatments.

Methods

Site Description

The study area was located on the Cold Hill Area of the London Ranger District of

Management and Policy Implications

Two key parts of a forest restoration project include setting defined endpoints and conducting activities within existing policy and administrative guidelines. We found that conducting research on a National Forest with a litany of cooperators was best accomplished when proposed activities were delineated in an approved forest plan, when research and management activities were congruent with national policy considerations, and when long-term commitments for planning, implementation, and monitoring are sustained. Although much is known about the silviculture and ecology of eastern upland oak systems, as well as about the impacts of oak decline and the gypsy moth (*Lymantria dispar* L.), the transfer of this knowledge to a system on the Cumberland Plateau in eastern Kentucky had not been tested. Our goals were to take an existing forest plan that captured myriad silvicultural strategies, marry it with replicated, stand-level research implementation, and use knowledge gained in a preemptive attempt to mitigate potential negative consequences on the health and sustainability of the forest. Initial results show that we can influence stand structure and composition as well as the distribution of regenerating cohorts that have the ability to withstand the disturbance regime associated with gypsy moth defoliation and oak decline. The study also tested mechanisms to overcome fiscal challenges associated with some treatments, including the use of stewardship contracting to help defray costs.

Table 1. Silviculture prescription descriptions for five treatments applied to stands on the Daniel Boone National Forest, Kentucky.

1. Shelterwood with reserves
This treatment left a residual basal area of 10-25 ft^2 $acre^{-1}$. Residual trees were selected to promote increased forest health conditions and to improve habitat for wildlife and plant species that benefit from open, low basal area forest conditions. Oak species were favored. A new stand will regenerate beneath the reserve trees and eventually create a two-aged stand structure.
2. Oak shelterwood
This treatment did not initially impact the overstory basal area. All basal area was removed from the midstory and understory without making canopy gaps in the overstory. Undesirable tree species <3 in. dbh were treated with a thinline basal bark treatment using triclopyr ester. Trees >3 in. dbh in the midstories and understories were treated with a stem injection method using triclopyr amine. Undesirable tree species included those specifically in competition with oaks, such as red maple and yellow-poplar, and trees with unhealthy stems and/or crowns. When sufficient advanced oak regeneration is present, the overwood will be removed to create a new even-aged oak-dominated stand (Loftis 1990).
3. Thinning
This treatment used the Gingrich stocking chart to thin to B-level stocking (Gingrich 1967). Reducing tree density allowed the residual trees to take advantage of improved growing conditions. The result should be increased tree vigor, larger crown diameters, continued or improved diameter growth, and increased capacity to survive defoliation. The thinning treatment was marked using crown vigor guidelines as well as stocking goals to match the presalvage thinning prescription (Gottschalk 1993, Gottschalk and MacFarlane 1993).
4. Oak woodland
This treatment was conducted by first thinning to 45–70 ft^2 $acre^{-1}$ followed by prescribed burning every 3–5 years. White oaks were favored as residual trees to increase hard mast production and bat habitat. An objective of the treatment was spatial and vertical heterogeneity. Another objective was to increase the native ground flora of forbs and grasses that are fire dependent. Prescribed burns will be operational spring burns conducted by Daniel Boone National Forest personnel.
5. Control
This treatment did not receive a silvicultural prescription and will be used to compare and evaluate the results of change from the above treatments.

the DBNF. The treatment stands were located on the Central Escarpment (221Hb) landtype association, as described in the Land and Resource Management Plan (USDA Forest Service 2004, p. 1-8). All treatment stands were located on broad ridges. Treatment stands were relatively similar before treatment and uniform within stand boundaries and were best described as upland hardwood forests dominated by oak species. Stands ranged in size from 16 to 48 acres, with an average size of 25 acres. Total basal area ranged from 100 to 120 ft^2 $acre^{-1}$, relative stand density ranged from 60 to 104%, and ages ranged from 70 to 150 years old. Forest types were randomly distributed but represented fixed factors: submesic (site index for upland oaks estimated to be 65–80 ft at base age 50) and subxeric (site index 50–65 ft) oak forests (Smalley 1986). The stands have been subjected to various silvicultural treatments, including harvesting and prescribed burning, since the USDA Forest Service acquired the land in 1937, but the stands are representative of fully stocked upland hardwood forests on the Cumberland Plateau.

Treatments

The experimental design for this study was a completely randomized design, with a 2 × 5 factorial treatment arrangement. Treatments were implemented at the stand level, and stands were randomly chosen from a pool of potential stands located across the landscape. Treatment assignments, however, were restricted for some stands due to administrative or logistical concerns (e.g., prescribed burns could not be conducted in stands near residential in-holdings), but pretreatment reconnaissance data did not indicate bias from nonrandomization of some treatment assignments. Stand boundaries were delineated based on several factors, including administrative constraints, proximity to road infrastructure, stand history, ownership boundaries, topography, soil type, and species composition. Site type was a treatment factor with two levels (subxeric or submesic), and the other treatment factor was silvicultural treatment with five levels: (1) shelterwood with reserves, (2) oak shelterwood, (3) thinning, (4) oak woodland, and (5) a control (Table 1). The five silvicultural treatments were randomly assigned to 15 stands within each of the two site types (30 stands total). Thus, 10 treatment conditions were replicated across the landscape in the Cold Hill Area, London Ranger District, DBNF (Figure 1).

A mechanical cut-to-length harvesting system was used to harvest all stands in the shelterwood with reserves, oak woodland, and thinning treatments. Control and oak shelterwood stands were not harvested. The system consisted of a feller-buncher, a grapple skidder, and a knuckleboom loader. Trees larger than 23 in. dbh were felled with a chainsaw. All limbing and topping were performed with a chainsaw in the stand. Products removed from the stands included hardwood sawtimber and biomass logs. A biomass log was any material >3 in. dbh that was reasonably straight, was at least 10-ft long, and did not qualify as a sawlog. Harvesting began in November 2007 and was completed for all 18 stands (excluding the control and oak shelterwood stands, which did not receive a harvest treatment in 2007–2009) in September 2009. Herbicide treatment for the oak shelterwood stands was done between October 2008 and March 2009. Undesirable tree species <3 in. dbh were treated with a thinline basal bark treatment using triclopyr ester. Trees >3 in. dbh in the midstories and understories were treated with a stem injection method using triclopyr amine.

Data Collection

Because gypsy moth defoliation and oak decline events are known to induce compositional changes to both the overstory (direct) and understory (indirect by release of subcanopy trees due to canopy tree decline or death), we designed field sampling to capture numerous changes in the structure and composition of these two layers. We established 20 0.1-acre vegetation measurement plots in each stand and measured plots before and 1 and 3 years after treatment implementation. All plot centers were permanently marked with rebar and global positioning system (GPS) coordinates were captured for each. We permanently labeled all trees ≥4.6 in. dbh. For overstory trees (≥4.6 in. dbh), we recorded and measured species, dbh, crown class position (open grown = 1, dominant = 2, codominant = 3, intermediate = 4, and overtopped = 5), tree vigor (see Table 2 for tree vigor descriptions), and canopy cover. Tree vigor metrics that incorporated crown conditions and crown class position have been used to access tree health in forests affected by oak decline or gypsy moth (Starkey et al. 1989, Gottschalk 1993, Oak et al. 1996). Within each 0.1-acre plot, we established a 0.01-acre subplot where we enumerated regeneration (trees <1.5 in. dbh) by species and height class. For posttreatment in the oak shelterwood treatment only, we surveyed

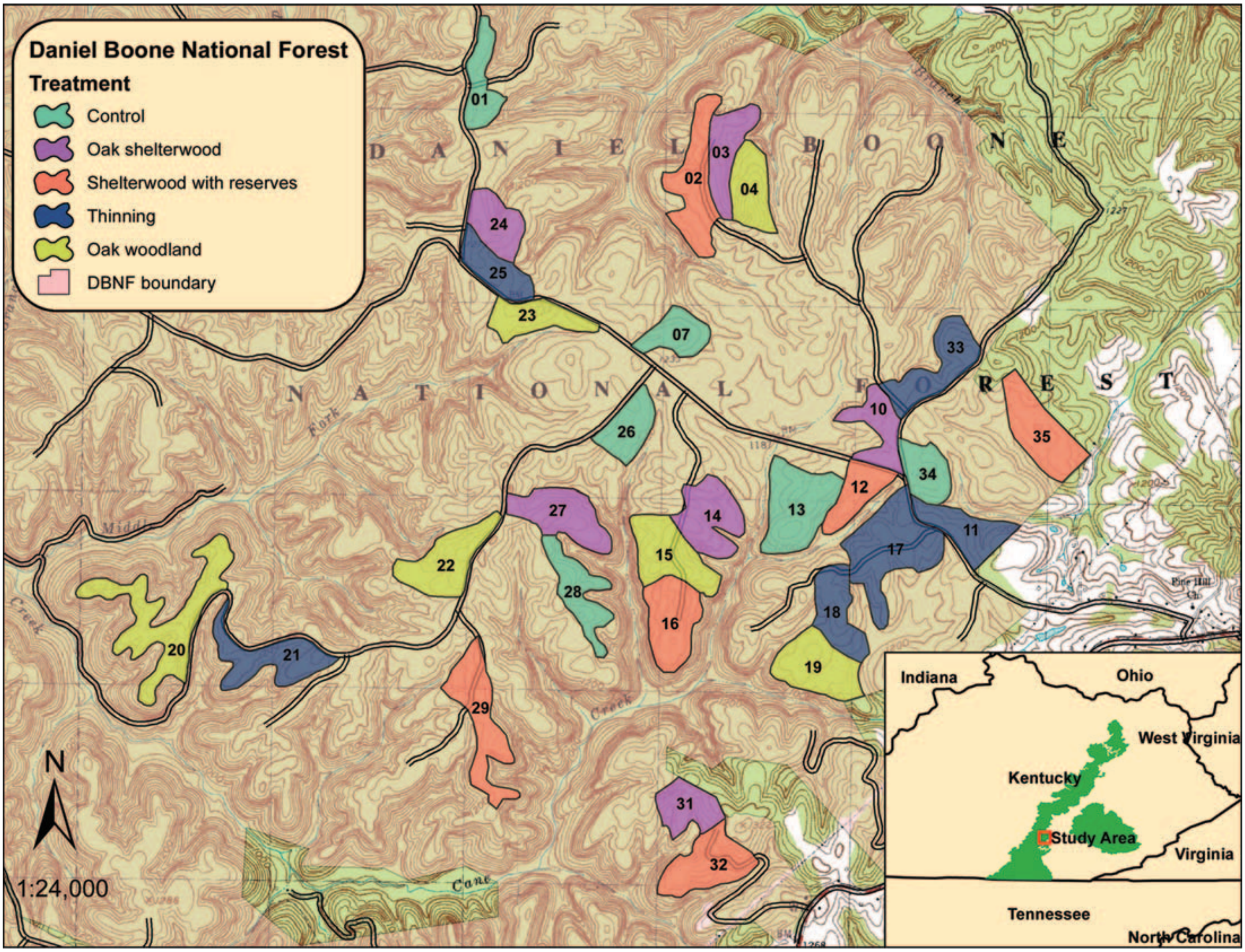

Figure 1. Distribution of treatments across the Cold Hill District, Daniel Boone National Forest, Kentucky. Treatment descriptions are given in Table 1. Each treatment was replicated six times across the landscape.

Table 2. Vigor rating based on tree crown and bole condition to assess tree vigor on the Daniel Boone National Forest, Kentucky.

Class	Vigor				
	% dead branches	Crown assessment	Foliage description	Epicormic branching	Stump sprouts
1: Healthy	0–10	Healthy	Dense; green	None	None
2: Good	11–25	Good	Density subnormal	Few	None
3: Fair	26–50	Fair	Density and color subnormal	Some	None
4: Poor	51–80	Poor	Density, color and size subnormal	Heavy	None
5: Very poor	81–100	Very poor, apparently dying	Extremely sparse	Tree living on sprouts	None

Crown and bole conditions were adopted from Gottschalk (1993).

status, species, and dbh for all stems ≥1.6 in. on five 0.025-acre plots to assess the effectiveness of this treatment for killing stems in the midstory (trees ≥1.5 in. but <4.5 in. dbh). To assess harvesting machine productivity, data recorders were attached to the harvesting machines and recorded gross harvesting time for each treatment subjected to harvesting. A portable digital recorder and small camera were used to help quantify the number and type of loads for analysis of truck loading and turn times, and these data were then used to calculate an estimate of cost and efficiency (Thompson et al. 2011).

Analysis

Because treatment stands were chosen from a larger population of stands available, replications of treatments were treated as random within the analysis, but we recognize that not all treatment assignments were truly random, as described above. Site type and silvicultural treatment were fixed effects. Because of the relatively large area occupied by each treatment stand (average stand size was 25 acres, with a range from 17 to 48 acres), the assumption of independence be-

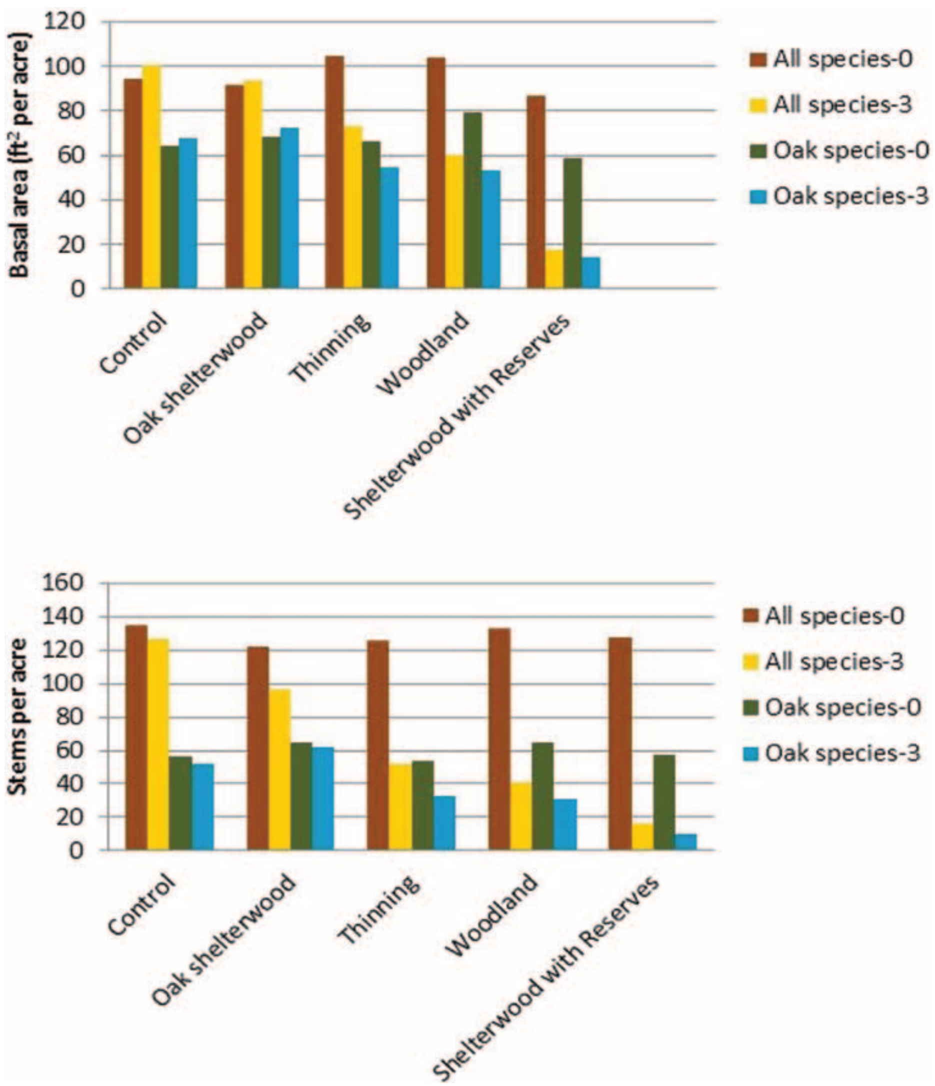

Figure 2. For all species and for oak only, pretreatment (−0) and 3-year posttreatment (−3) BA (top) and SPA (bottom) for five treatments (control, oak shelterwood, thinning, woodland, and shelterwood with reserves) on the Daniel Boone National Forest, Kentucky.

tween treatments is supported. A mixed model (PROC MIXED) analysis of variance was used to test the statistical significance of treatment main effects and their interactions; the *P* value at the 0.05 significance level initiated further analyses of mean separations within the treatment or treatment combinations. Dependent variables in the analysis included basal area (BA) for overstory trees and stems per acre (SPA) for overstory and regeneration. Treatment effects and interactions were also analyzed for vigor rating for each sawtimber size class; saplings (1.8–5.5 in. dbh), poles (5.6–11.5 in. dbh), small trees (11.6–17.5 in. dbh), medium trees (17.6–23.5 in. dbh), and large trees (≥23.6 in. dbh). BA, SPA, and crown vigor variables were analyzed separately for all species combined and for all oak species combined. We used Duncan's new multiple range test post hoc to separate means. All analyses were performed using SAS version 8.01 (SAS Institute, Inc. 2000).

Results

Overstory Density and BA

Before treatment, we identified 30 different species in these stands (data not shown). The *Pinus* genera were dominated by shortleaf pine (*Pinus echinata* Mill.), with a smaller proportion of Virginia pine (*Pinus virginiana* Mill.) and pitch pine (*Pinus rigida* Mill.). Four eastern hemlock trees (*Tsuga canadensis* [L.] Carr.) per acre were tallied, with the majority in the pole-size class (dbh between 5.6 and 11.5 in.). Other species included upland oaks (chestnut oak, white oak, northern red oak, scarlet oak, southern red oak [*Quercus falcata* Michx.], blackjack oak [*Quercus marilandica* Muench.], post oak, and black oak), hickories (shellbark hickory [*Carya laciniosa* Schneid.], shagbark hickory [*Carya ovata* K. Koch.], and mockernut hickory [*Carya tomentosa* Nutt.]), red maple, sourwood, and lesser amounts of species such as yellow-poplar and blackgum (*Nyssa sylvatica* Marsh.).

We found no significant differences for BA (in ft^2 acre^{-1}) ($P = 0.07$) and SPA ($P = 0.20$) among the five silvicultural treatments or between the two site types before treatment implementation (Figure 2). BA ranged from 91.4 to 104.5 ft^2 acre^{-1} (SD 4.6–12.0), and SPA ranged from 122–135 (SD 15–25) before treatment implementation. There were no significant differences for BA ($P = 0.43$) and SPA ($P = 0.08$) for stands originally identified as submesic, which had average BA of 100.5 ft^2 acre^{-1} (SD 9) and 128 (SD 1.5) SPA compared with that for subxeric stands, which had BA of 110.7 ft^2 acre^{-1} (SD 7.2) and 124 (SD 4) SPA. There were no treatment × site interactions.

Three years after treatment, silvicultural treatments significantly differed in BA and SPA for all species combined ($P = 0.04$ for BA and $P = 0.03$ for SPA) and for oak species ($P = 0.02$ for BA and $P = 0.02$ for SPA) (Figure 2). The shelterwood with reserves treatment had significantly less BA and SPA compared with those for the other four treatments ($P = 0.02$) with 17.5% BA and 16 SPA. The thinning treatment had significantly greater BA than the oak woodland and shelterwood with reserves ($P = 0.01$) treatments with ~30 SPA of oak and ~50 SPA of other species and ~55% BA of oak species and 70 BA of other species. Control and oak shelterwood stands did not differ in either BA or SPA for all species combined and for oak species. Oak BA increased from 76.1 to 89.3% of the total BA for the oak woodland treatment and from 67.8 to 79.5% in the shelterwood with reserves treatment.

The thinning treatment reduced BA from 104.5 to 73.3 ft^2 acre^{-1}, and SPA changed from 126 to 52. Using the stand density guide of Gingrich (1967), which incorporated measures of BA, number of trees, and average tree diameter to estimate stocking percentage, our stands were taken from nearly 100% stocked (A-line) to just above 60% stocked (B-line), as was the objective. The majority of the removed stems were taken from the pole-sized diameter class (49 SPA removed), although stems were re-

Table 3. Regeneration stems per acre by height classes, pretreatment (time = 0) and 3 years posttreatment (time = 3) for the control and three potential regeneration treatments applied to stands on the Daniel Boone National Forest, Kentucky.

Height class	<1 ft tall		>1 ft-4.5 ft		>4.5 ft-1.5 in. dbh		Total	
Time	0	3	0	3	0	3	0	3
Control								
All species	294	1,107	148	260	43	60	485	1,427
Oak	73	138	30	74	1	4	104	216
Red maple	83	711	44	65	19	20	146	796
Oak shelterwood								
All species	262	710	120	229	36	69	417	1,008
Oak	69	83	24	47	1	4	90	133
Red maple	72	512	42	76	16	31	131	618
Oak woodland								
All species	323	420	100	233	22	38	455	691
Oak	76	125	12	61	0	2	88	188
Red maple	78	113	50	69	8	25	136	206
Shelterwood with reserves								
All species	281	212	110	222	35	191	426	624
Oak	62	39	28	46	1	17	92	103
Red maple	73	52	25	53	13	53	111	158

moved from all diameter classes except the large sawtimber class (dbh ≤23.6 in.).

Regeneration

In the oak shelterwood treatment, we injected with herbicide 176 SPA that averaged 3.0 in. dbh and ranged from 1.6 to 9.1 in. dbh. Of the stems treated with herbicide, 60% were red maple, 7% were yellow-poplar, and the remaining 33% were a combination of various species including blackgum, sourwood, sassafras, bigleaf magnolia (*Magnolia macrophylla* Michx.), and serviceberry (*Amelanchier aborea* [Michx. f. Fern.]). The residual stands are composed of primarily oaks (77.8% of residual stem density was oak), red maple (11%), and hickories (5%) with a lesser component of shortleaf pine, yellow-poplar, sourwood, and flowering dogwood (*Cornus florida* L.) (6%). The oak regeneration cohort in the oak shelterwood treatment increased by 43 SPA after three growing seasons and totaled 133 SPA; the most prominent competitor, red maple, increased by 488 to 618 SPA. The majority of red maple stems were <1 ft tall (512 of the 618 SPA total) (Table 3).

The number of oak seedlings increased in the shelterwood with reserves treatment, with the most prominent increase noted in the largest size class, those stems >4.5 ft tall but <1.5 in. dbh, which increased from one SPA to 17 (Table 3). Congruently, red maple stems in this largest size class increased by 40 SPA, from 13 to 53 SPA. Both oak and red maple increased in the oak woodland treatment, with the increases distributed across all size classes. These assessments were made before the first prescribed burn of the oak woodland treatment.

Canopy Cover

After three growing seasons, a gradient of canopy cover followed the control, oak shelterwood, and thinning treatments (94.7, 91.9, and 84.9%), which was greater than that for oak woodland and shelterwood with reserves treatments (72.6 and 69.1%). A detailed analysis of the understory light regimes for three of the treatments can be found in Grayson et al. (2012). They reported that spatial and temporal distribution of light in the treated stands varied greatly, but simple linear regression relationships were found between BA and canopy cover. As expected, canopy cover decreased with treatment intensity. Mean canopy cover in the control treatment was approximately 2 times greater than that in the shelterwood with reserves treatment. BA explained 85% of the variation in mean canopy cover, and this was further reflected in the amount of full ambient light reaching the understory, which ranged from 9% for the control to 29% for the thinning to 68% for the shelterwood with reserves treatments.

Tree Vigor and Crown Position

The oak shelterwood stands had a significant increase in tree vigor and crown class for all species assessed and for only oak species (Table 4). Most of the midstory deadened was pole- and sapling-sized stems of red maple and yellow-poplar. Sapling vigor in this treatment decreased by 1.15.

In the thinning treatment, vigor class for both small and medium sawtimber decreased after treatment (Table 4). Medium sawtimber-sized trees were released, and their crown position class increased from 2.96 (generally in codominant positions) to 1.83 (dominant to open-grown). Across all size classes and species, vigor declined by 0.4, although large sawtimber, poles, and saplings averaged higher vigor ratings 3 years posttreatment (Table 4). Conversely, for oaks, vigor assessment values showed an increase in residual vigor and crown class. There were few noted epicormic branches in all tree classes, with less than one large sawtimber tree per acre having an average of four epicormic branches per tree and three medium sawtimber trees per acre having two epicormic branches per tree. The majority of the medium sawtimber trees displaying epicormic branching were white oak, black oak, and scarlet oak. There were few wounds on the lower boles of residual trees, with three small sawtimber trees per acre with 2 to 1,000 in.^{2} wounds and <1 wounded tree per acre for the medium and large sawtimber trees.

Removal of pole-sized trees in the oak woodland treatment and a preference for residual oak resulted in an increase in crown position by one level for all residual trees, including oaks. The vigor class for residual trees in the oak woodland stands was similar to that of the pretreated stands for all sizes except medium sawtimber of all species and saplings of all species, which declined in vigor (Table 4). The proportion of oak in

Table 4. For all species and for oak only, pretreatment (−0) and 3-years posttreatment (−3) vigor rating and crown class assessment by sawtimber classes for five treatments (control, oak shelterwood, thinning, woodland, and shelterwood with reserves) on the Daniel Boone National Forest, Kentucky.

	Sawtimber class and species group											
	Large (dbh ≥23.6 in.)		Medium (dbh 17.6–23.5 in.)		Small (dbh 11.6–17.5 in.)		Pole (dbh 5.6–11.5 in.)		Sapling (dbh 1.8–5.5 in.)		Average	
	All	Oak	All	Oak	All	Oak	All	Oak	All	Oak	All	Oak
Control												
Vigor-0	1.98	1.97	2.07	2.09	1.87	1.87	1.99	2.01	2.32	2.20	2.05	2.03
Vigor-3	1.90	2.11	2.84	1.34	1.50	1.50	1.75	2.03	2.12	2.43	2.02	1.88
Crown-0	2.71	2.70	1.78	2.86	3.12	3.08	4.11	3.91	4.53	4.48	3.25	3.41
Crown-3	2.38	2.27	2.50	2.67	2.88	2.80	3.92	3.77	4.33	3.93	3.20	3.09
Oak shelterwood												
Vigor-0	2.23	2.23	1.97	1.99	1.82	1.84	1.95	1.86	2.13	2.16	2.02	2.01
Vigor-3	1.29	2.15	1.47	1.42	1.27	1.30	1.96	1.62	3.28	1.90	1.85	1.68
Crown-0	2.53	2.49	2.67	2.65	3.12	3.03	4.16	4.02	4.64	4.68	3.42	3.37
Crown-3	2.53	2.10	2.37	2.59	2.85	2.82	3.85	3.76	4.19	4.49	3.16	3.15
Thinning												
Vigor-0	1.52	1.50	1.57	1.60	1.51	1.58	1.78	1.82	2.09	2.33	1.69	1.77
Vigor-3	1.30	2.75	2.75	1.30	3.28	1.26	1.69	1.63	1.44	1.00	2.09	1.59
Crown-0	2.87	2.85	2.96	2.96	1.28	3.09	4.31	4.02	4.73	4.44	3.23	3.47
Crown-3	2.40	1.80	1.83	2.46	2.70	2.62	3.54	3.50	4.28	4.60	2.95	3.00
Woodland												
Vigor-0	2.07	2.09	1.96	1.95	1.98	1.97	2.08	1.99	2.34	2.33	2.09	2.07
Vigor-3	2.06	3.00	3.88	1.86	1.81	1.89	1.82	1.82	2.88	1.44	2.49	2.00
Crown-0	2.82	2.81	2.79	2.78	3.06	3.01	4.10	3.86	4.60	4.51	3.47	3.39
Crown-3	2.25	1.84	1.50	0.28	2.57	2.52	3.61	3.33	4.38	4.22	2.86	2.88
Shelterwood with reserves												
Vigor-0	1.98	1.98	1.76	1.79	1.65	1.69	1.87	1.88	2.19	2.04	1.89	1.88
Vigor-3	1.90	5.72	5.91	1.65	1.65	1.59	2.07	2.11	2.23	1.40	2.75	2.49
Crown-0	2.71	2.71	2.72	2.68	3.17	3.07	4.22	3.98	4.65	4.53	3.49	3.40
Crown-3	2.38	1.80	0.42	1.92	2.00	2.02	2.72	2.58	3.15	2.80	2.13	2.22

Vigor rating descriptions are given in Table 2. Crown classes are defined as 1 = open grown, 2 = dominant, 3 = codominant, 4 = intermediate, and 5 = overtopped.

the residual stands increased for all size classes and residual oaks increased their vigor rating except the 4 SPA of large sawtimber. Incidence of epicormic branching increased from one residual tree per acre to between four to six residual trees per acre in large, medium, and small sawtimber classes, accounting for the vigor rating decline. The trees displaying epicormic branching were again primarily white oak, black oak, and scarlet oak. Residual pole-sized trees had the greatest bole damage, with 5 SPA damaged; 4 SPA were damaged in the small sawtimber class, 3 SPA were damaged in the medium sawtimber class, and <1 SPA was damaged in the large sawtimber class.

After harvesting, the nonoak trees declined in vigor class by 0.86 in the shelterwood with reserves treatment, whereas the large sawtimber oaks decreased by 3.74 (Table 4). The residual stands had only eight large sawtimber trees total; one residual white oak, which was codominant with a crown vigor of 1.0, had over 200 epicormic branches posttreatment and two other residual trees had large bole wounds (600 and 18 in.^{2}, respectively). Medium sawtimber trees had few boles with epicormic branches (less than one tree per acre), and little damage was noted. For all species combined and for oak only, residual trees were less vigorous, and trees were close to being classed as open grown.

Harvesting Productivity

Harvesting was completed with a mechanical harvesting system using two separate contractors. A second contractor was added in late 2007 when it became clear that the productivity was hampered by wet weather conditions and the desired completion date was in jeopardy. Harvesting system machine type and costs are given in Table 5. Products removed included hardwood sawtimber and biomass logs.

The shelterwood with reserves stands averaged 27 acres and took 9 weeks each to harvest and product removal percentages were closely split between biomass (54% of tons removed) and saw logs (46% of tons removed), as stems were taken across all diameter classes. This treatment also had the highest productivity (3.98 tons per productive machine hour). The oak woodland and thinning stands averaged 23.5 acres and took 4 and 5 weeks each to harvest. For the oak woodland, biomass was 65% of the tonnage removed and saw logs were 35%, and harvesting productivity was 3.88 tons per productive machine hour. The thinning treatment had the lowest productivity, 2.60 tons per productive machine hour, and the highest percentage of biomass removed (78%). We used a 2,000 hours/year scheduled hours for a machine to calculate an overall utilization rate based on recorded productive hours (Brinker et al. 2002). A gross system utilization rate of 25.7% was calculated for all harvested stands using recorded machine hours and the number of weeks spent in actual harvest activities.

Discussion

Planning

The planning of this project was highly affected by the diverse and numerous partners (Table 6). The initial study proposal was met with some consternation; that the project was under the auspices of research and preemptive was not broadly communicated at the onset of the study and may have contributed to the confusion. We speculate that heightened public concern regarding the scientific merit and management objections in this study derived from the antidotal or correlative application of western forest response to preventative management for reducing risk associated of damage due to insect infestations[1] and from private citizens' groups generally opposed to logging on national forests. Additional delays were incurred after the ruling *Earth Island Institute v. Ruthenbeck* (Case CIV F-03-6386 JKS) by the Federal District Court for the Eastern District of California, which struck down the provisions that removed categorical exclusions from the notice, comment, and appeal regulations for management actions on national forests.

In January 2006, a notice went out to the public for review and comment on the study proposal. Comments were received and addressed, and a field day was held for interested parties. During the field day, researchers were introduced and further explained the design and long-term, preemptive nature of the study. After considerable effort by the managers and researchers involved, a decision was rendered by the Acting Forest Supervisor that stated "under the authority of the *Healthy Forest Restoration Act of 2003* (HFRA)–HFRA Sec 404 applied silvicultural treatments, Section 404(d)(1) of the Act provides for categorically excluding from documentation in an environmental impact statement and environmental assessment under the National Environmental Policy Act of 1969 (NEPA), applied silvicultural assessments and research treatments carried out under this section. The environmental analysis is subject to the extraordinary circumstances procedures established by the Secretary pursuant to Section 1508.4 of title 40, Code of Federal Regulations" (USDA Forest Service 2006). Study implementation began in the summer of 2007.

Implementation

We used SILVA (Marquis and Ernst 1992) to assist with developing the marking guidelines for the harvesting treatments. Although not calibrated for systems in the Cumberland Plateau region, output results from the program were reviewed before implementation and appeared sound. We worked as a team to determine the most efficient way to mark the stands using SILVA guidelines, incorporating methods developed by the research crew and input from various biologists. The use of an accepted and field-tested program to quantify the prescriptions in a manner that would allow others to easily adopt and apply the prescrip-

Table 5. Harvesting system machine types and estimated costs for two contractors used to implement three different silviculture prescriptions on the Daniel Boone National Forest, Kentucky.

Machines and labor	Cost in US$ for productive hours
Contractor 1	
1999 John Deere 648G Grapple Skidder	53.31
1999 Timber jack 2618 Tracked Feller-Buncher	66.34
2007 John Deere 335 Knuckleboom Loader	75.01
Chainsaw	1.60
Manual laborer (wage + fringe benefits)	24.72
System	220.98
Contractor 2	
1998 John Deere 648G Grapple Skidder	53.31
1998 Timber jack 608 Tracked Feller-Buncher	66.67
1985 Hawk Knuckleboom Loader	36.24
Chainsaw	1.60
Manual laborer (wage + fringe benefits)	24.72
System	182.54

Table 6. List of partners involved in the design and implementation of a silviculture assessment study to mitigate potential impacts from gypsy moth defoliation on the Daniel Boone National Forest, Kentucky.

Organization	Division	Location	Role
USDA Forest Service, Daniel Boone National Forest	Cold Hill District, Supervisor Office staff	London, KY and Winchester, KY	Field site selection and implementation
USDA Forest Service, Southern Research Station	Research Work Units SRS-4157 and SRS 4703	Huntsville, AL and Auburn, AL	Forest dynamics; bats; harvesting utilization
USDA Forest Service, Northern Research Station	Research Work Unit NRS-003	Morgantown, WV	Forest health
USDA Forest Service, Region 8	Forest Health Protection	Asheville, NC	Forest health
USDA Forest Service, Washington Office	Ecosystem Management	Washington, DC	Policy
University of Kentucky	Department of Forestry	Lexington, KY	Forest dynamics and implementation
University of Tennessee	Forestry, Wildlife and Fisheries	Knoxville, TN	Light parameters; light detection and ranging (LiDAR); American chestnut
Eastern Kentucky University	Cumberland Laboratory of Forest Science, Department of Biological Sciences	Richmond, KY	Dendroecology; bats
Kentucky Wesleyan College	Department of Biology	Owensboro, KY	Insects
Kentucky Division of Forestry		Frankfort, KY	Forest management
Kentucky Department of Fish and Wildlife Resources		Frankfort, KY	Wildlife impacts; bats; migratory birds
East Kentucky Power Cooperative		Winchester, KY	Harvest utilization and biomass
Kentucky Forest Industries Association		Frankfort, KY	Harvest utilization
American Chestnut Foundation		Asheville, NC	American chestnut restoration
Bluegrass Woodland Restoration Center LLC		Lexington, KY	Woodland restoration
Kentucky Heartwood		Berea, KY	Forest health
National Forest Protection Alliance		Spokane, WA	Forest protection

tions provided an additional benefit for partners. We used detailed stand-level program outputs that provided metrics for marking specific trees, by species and diameter classes, that resulted in a gradient of residual stands that represented, as a desired ancillary outcome, a host of habitat characteristics.

For example, there was concern over the potential impact of timber harvesting on communities of bat species of federal or state management importance, e.g., Indiana bats (*Myotis sodalis*), gray bats (*Myotis grisescens*), Virginia or Rafinesque's big-eared bats (*Corynorhinus townsendii virginianus*, *Corynorhinus rafinesquii*), and Eastern small-footed bats (*Myotis leibii*). Before we could assess whether bats changed their habits or habitats in response to timber harvesting or prescribed fire, we had to implement the harvesting in compliance with US Department of the Interior Fish and Wildlife guidelines (USDA Forest Service 2004), which gave detailed instructions on the number of snags to be retained, the needed requirements of shade for those residual snags, and species retention requirements. Of concern was the potential conflict between leaving bat roost trees, which had characteristics such as sloughing bark or cavities with openings to the outside, e.g., large splits or cracks in the bole, large broken limbs, or lightning scars, and leaving trees of higher vigor, which had characteristics opposite to these. With our SILVA outputs and wildlife guidelines in hand, we spent a considerable amount of time discerning how to mark each stand. We also worked in concert with several bat biologists to document the habitat characteristics and use by the indigenous bat community. Six bat species have been identified in the treatment stands, and the treatments appear to be having a positive effect on bat activity (Susan Loeb, USDA Forest Service, Southern Research Station, pers. comm., Nov. 21, 2013). The oak shelterwood treatment showed the lowest change in bat activity posttreatment, whereas thinning showed the highest change. Both the thinning and shelterwood with reserves stands showed a spike in bat activity immediately after treatment, which then leveled off in the following 2 years.

Finalizing harvesting involved many more partners than we originally had planned. Another research and management objective was to ascertain the costs and operational performance under a mechanized forest operation that was to also incorporate removal of material considered "biomass." In short, the biomass was destined for a local woodyard, but the buyer rejected the material and an alternative buyer, located further away, had to be procured. Because the biomass market is not well developed in this area, interest was low. We used two different contractors to complete the harvests, and the productivity of the harvesting systems was low, as others reported 4–30 times the productivity found in our study (Sarles and Whitenack 1984, Long et al. 2002). If biomass harvesting is to be incorporated in eastern hardwood forests, the volume of the small diameter stems removed will greatly affect the harvest productivity. Continuing struggles to contract harvesting and purchasing of these materials is also of concern.

Resilience to Gypsy Moth and Long-Term Sustainability

We created a gradient of residual stands that will allow us to monitor stress induced by the gypsy moth or other factors to incite oak decline. Initial stand conditions in this study were characterized by oak-dominated, fully-stocked stands, which had crown vigor ratings in the lower range of fair-to-good crowns. Oak species were initially rated lower in vigor compared with the suite of species found in the entire stand, but after treatment, vigor increased slightly for oaks in all treatments except the shelterwood with reserves, but including the control. Ratings for oaks never increased to the healthy class regardless of treatment.

For the three treatments that were subjected to harvesting, the saplings, poles, and small- and medium-sized residual oak sawtimber generally improved their vigor ranking and canopy positions compared with those of the pretreatment population. This should allow for continued growth of these oak trees into large overstory trees and they should be generally healthier and have lower chance of mortality during oak decline or gypsy moth attacks than under pretreatment conditions (Eisenbies et al. 2007). Several concerns remain, however, including the continued dominance in these stands by oak, a known susceptible species (adapted from Gottschalk 1993), and the decrease in vigor of large sawtimber oak and medium sawtimber trees of other species, particularly in the oak woodland and shelterwood with reserves treatments. In addition, thinning did not improve the vigor of small sawtimber sized nonoak trees. Perhaps the most important concern is that the oak woodland and shelterwood with reserves treatments had lower or similar vigor in large, medium, small, and pole size oak trees compared with that in the control or oak shelterwood treatments. Saplings of all species, including oak, did not improve the most in vigor, compared with the other size classes, from harvesting, particularly in the thinning treatments. Interestingly, the midstory removal in the oak shelterwood treatment did not improve vigor or crown class of saplings or pole size oak over what was found in the thinning treatment.

The creation of oak woodlands in these upland hardwood forests required some blending of known silvicultural prescriptions with values regarding restoration of a prehistoric forest condition. The Land and Resource Management Plan (USDA Forest Service 2004) referenced the classification of Grossman et al. (1998) as justification for woodland as one desired future condition area. Creation of woodlands with a dependence on frequent fires to create and maintain a grass-dominated understory has gained heightened attention in the region, based on pre-European landscape benchmarks. Delcourt et al. (1998) provided the most detailed research into Native American populations and activities in eastern Kentucky. They found that there was an absence of Native Americans on the Cumberland Plateau between AD 1500 and 1750, with most settlements around major water sources. Their impact on the forest vegetation, as derived from fossil pollen assemblages, postulated small, cleared forest gaps, with fires as relatively localized events. Recent research challenges the predominant view of fire as the main disturbance in upland hardwood forests due to anthropogenic influences since the last glacial retreat (Nowacki and Abrams 2008) and suggests that fire was closely linked to climate, particularly drought (Matlack 2013). Upland oak-hickory forests dominate the Cumberland Plateau, with most standwide release events characterized as small-scale events that may contribute to these forests succeeding to maple and other mesic species dominance (Hart and Grissino-Mayer 2008, Nowacki and Abrams 2008, Hart et al. 2012). We were able to take a conservative approach to the initial creation of an oak woodland, which resulted in stands dominated by oak (31 of the 41 residual SPA), and these residual oak in the 11.6–23.5 in. dbh class did have higher vigor and crown class ratings than pretreatment trees in the same stand.

Prescribed fire during the dormant season has been implemented one time since the harvest; no assessments have been made postburn. However, low-intensity prescribed fires seldom cause mortality in overstory trees (Waldrop et al. 1992, Barnes and Van Lear 1998, Dey and Hartman 2005, Hutchinson et al. 2005, Blankenship and Arthur 2006). Although we are not yet to the stage to begin the regeneration process in these stands, we did have an impact on the regeneration. Advanced regeneration of large oak (≥4.5-ft tall) was increased posttreatment, but the numbers remain woefully low at 6 SPA compared with the recommended 430 SPA to sustain oak (Gottschalk 1993). The subsequent increase in the abundance of red maple in the understory makes the success of oak regeneration uncertain at this stage.

Large oak regeneration in the shelterwood with reserve treatment was also low (24 SPA) but did increase from 2 SPA pretreatment. We implemented an additional tending treatment 1 year postharvest that followed Miller et al. (2006), and released oak advanced reproduction before its suppression. Using a contractor, oaks that were between 2- and 4-ft tall were released from all surrounding vegetation within a 3-ft radius of the crop tree crown via basal stem herbicide treatment. Additional tending treatments may be necessary to release competitive oak in the understory and facilitate its recruitment into the overstory.

Conclusion

Although Gottschalk (1993) recommended treatment 1–3 years before a gypsy moth defoliation event, stakeholders on the DBNF realized that the time to act was in conjunction with the implementation of a new forest management plan. Even with an approved plan, it took several years to find consensus among the stakeholders and then to apply the prescriptions, because several of them are multiphase treatments that will require many additional years to complete. Implementation was complicated by policy and conflicting objectives. For example, the recommendations to create optimal habitat for bats and the desire to create oak woodlands, resulted in a direct conflict with the goal of decreasing stand susceptibility to gypsy moth events; namely, bats and oak woodlands required promoting the gypsy moth's preferred species, oak, and leaving large, overmature trees more prone to forest health problems. Biomass removal was highly touted as an objective, but the efficacy of removing smaller diameter materials was dismal. Unexpected low harvesting productivity should be noted and integrated into forest management planning. The lack of local markets for small diameter biomass products was also a deterrent. The thinning treatment resulted in the most favorable conditions for resiliency of these oak-dominated stands to gypsy moth-induced stresses. Oak residual trees increased their crown positions to more dominant ones, decreasing vulnerability to mortality (Gottschalk 1993) and resulting in a generally more robust stand. All treatments had an impact on the regeneration cohort, which trended toward higher densities of red maple than those of oak and with the red maple in more competitive positions after the initial treatments. Monitoring the vigor of the residual stands, which still have an abundance of oaks, and applying additional treatments to favor the regeneration of oak, will be paramount to the sustainability of these upland hardwood forests.

Intentions to implement long-term multidisciplinary projects has been long heralded, especially by the USDA Forest Service (Peterson and Maguire 2005). The development and implementation of such projects, however, are challenging. Communication is the most important task of leaders of the silvicultural research projects to combat these challenges. Communication is required to efficiently coordinate logistics to ensure completion and nonconflict between management and research operations and procedures (e.g., ensuring that pretreatment data collection is complete before harvesting begins). Communication is also required to bring consensus on implementation strategies, definitions of research, and management terms (e.g., ensuring that researchers are aware that marking guidelines require leaving certain tree species or size classes for threatened or endangered species). A challenge in this study also included waning interest over time that contributed to additional difficulties in meeting long-term targets. For forest management research, multidisciplinary studies are made easier because division of the objectives and subsequent work follow along disciplinary lines, and research objects are complementary and not overlapping. Because the USDA Forest Service has adopted management that targets myriad endpoints, approved management plans should be used as the basis to implement multidisciplinary research. Developing partnerships among researchers and managers within the framework of a National Forest management plan provides those involved with the congruency needed to accomplish both short- and long-term goals, within a background of national level recognition and support.

Endnote

1. For more information, see Gazette Times, 2005, www.gazettetimes.com/articles/2005/10/06/news/thewest/thuwst02.txt and www.gazettetimes.com/articles/2005/10/06/news/thewest/thuwst01.txt.

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