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Fuel reduction treatments affect stand structure of hardwood forests in Western North Carolina and Southern Ohio, USA

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Abstract

Prescribed fire and mechanical treatments were tested at the two hardwood sites of the National Fire and Fire Surrogate Study (southern and central Appalachian regions) for impacts to stand structure. After two fires and one mechanical treatment, no treatment or treatment combination restored stand structure to historical levels. Burning alone had little impact on overstory vegetation the first year after treatment but mortality continued for 4–5 years thus opening canopies. Thinning at the Ohio Hills site reduced stand basal area, but not to levels desired for restoration objectives. Chainsaw removal of the shrub layer at the southern Appalachian site reduced the midstory temporarily but promoted abundant regeneration. The combination of mechanical and burning treatments opened these dense forests the most, especially at the southern Appalachian site where hot fires killed overstory trees and promoted oak regeneration. Results from both study sites emphasize the rapid sprouting and growth of undesirable eastern species and the need for frequently-repeated treatments during the restoration phase.
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Keywords: Prescribed fire; Thinning; Overstory mortality; Southern Appalachian Mountains; Central Appalachian Plateau

1. Introduction

Contemporary ecosystems throughout the United States are highly altered from their historical conditions due to fire exclusion over the past century (Stanturf et al., 2002). As a result, forests with continuous canopies and sub-canopies developed over previously open grasslands, savannas, and woodlands (Buckner, 1983; Denevan, 1992; Dobyns, 1983; MacCleery, 1993, 1995; Pyne, 1997). Historically, hardwood ecosystems of the southern Appalachian Mountains and central Appalachian region have been described as having open canopies, few shrubs, and rich forest floor vegetation (Van Lear and Waldrop, 1989; Sutherland and Hutchinson, 2003); oak regeneration was more common than other species because of frequent fire (Brose and Van Lear, 1998). Restoration is a common goal which usually involves re-introduction of fire or mechanical means of altering stand structure. Eastern hardwood ecosystems were developed by a broad array of natural disturbances but the role played by natural and anthropogenic fire has not been appreciated until recent years (Brose et al., 2001). Considerable knowledge exists on the fire-dependent pine ecosystems of the western United States and the southeastern Coastal Plain (Brown and Smith, 2000; Smith, 2000; Sandberg et al., 2002; Neary et al., 2005). However, the role of fire is not well recognized for the Central Hardwood region and southern Appalachian Mountains (Waldrop et al., 2006). In these areas, prescribed burning programs and supporting research have lagged behind that of the west and southeastern Coastal Plain because of the perceived damage to hardwoods, difficulty of controlling high-intensity fires on slopes, and the potential for soil/site damage (Van Lear and Waldrop, 1989).

Lightning-caused fires have always been a component of eastern hardwood systems but fire frequency increased dramatically with the arrival of Native Americans about 10,000 years ago (Keel, 1976) and again as European settlers arrived in the early 1700s (Trimble, 1974). Timber companies

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began clearing land in the late 1800s and used uncontrolled fires to clear logging slash, a practice that initiated government fire exclusion policies in the 1920s. Although fire was never entirely missing from the eastern hardwood region, prescribed burning only began to be used in hardwood stands during the 1980s for site preparation (Phillips and Abercrombie, 1987) and in the 1990s for restoration of individual species (Waldrop and Brose, 1999) or multiple components of an ecosystem (Sutherland and Hutchinson, 2003). Most work in the region deals with initial impacts of fire or fuel reduction treatments on oak regeneration (Abrams, 1992; Loftis and McGee, 1993; Brose and Van Lear, 1998; Adams and Rieske, 2001) and changes to the herbaceous layer (Elliott et al., 1999; Hutchinson, 2006; Phillips et al., 2007). Little information is available for other resources (fauna, forest health, soils) or the impacts of treatments repeated two or more times.

In 2000, a team of federal, state, university, and private scientists and land managers designed the Fire and Fire Surrogate (FFS) study, an integrated national network of long-term studies to address the need for many types of information, with support from the USDA/USDI Joint Fire Science Program and the National Fire Plan (Youngblood et al., 2005). The national network includes 13 sites on federal and state lands extending from the Cascades in Washington to southern Florida. Similar experimental designs (randomized complete block or completely random designs) were used at all sites to facilitate comparisons of treatment effects on a broad array of variables including flora, fauna, fuels, soils, forest health, and economics (see, Youngblood et al., 2005 for a description of the national study). Most sites are dominated by conifer forests but two are located in the eastern hardwood region and directly address many questions of hardwood ecosystem restoration. The sites are in the southern Appalachian Mountains of western North Carolina and the central Appalachian region of southern Ohio.

Treatments at each site of the FFS Study are designed to restore ecosystems by re-establishing an ecosystem process (fire), stand structure (mechanical fuel reduction), or both. Although thinning and prescribed burning are often used to reduce the risks of wildfire and insect outbreaks, little attention has been paid to some of the ecological consequences of these management practices, particularly at an operational scale (Allen et al., 2002). Changes in stand structure can alter many ecosystem components such as vegetative diversity (Hutchinson, 2006), fire behavior and return interval (Phillips et al., 2006), soil processes (Boerner et al., 2006) and habitat for birds (Annand and Thompson, 1997; Baker and Lacki, 1997), mammals (Sullivan, 1979; Loeb, 1999), and invertebrates (Campbell et al., 2007; Whitehead, 2003).

This paper presents changes to stand structure and composition over a period of several years and after a variety of treatments on the two hardwood sites of the National Fire and Fire Surrogate Study, one in North Carolina and another in Ohio. At both sites, the primary management objective was to reduce severity of potential wildfires by reducing live and dead fuels. Secondary objectives were to increase oak regeneration by reducing competition from red maple (*Acer rubrum* L.) and yellow-poplar (*Liriodendron tulipifera* L); and to improve wildlife habitat by creating early-successional habitat, increasing cover of grasses and forbs, and improving oak regeneration. It may be possible to obtain each of these goals by restoring these communities to the open woodland habitats once common in these regions (described in syntheses by Stanturf et al., 2002 and Van Lear and Waldrop, 1989). Fire and mechanical treatments used at both sites were designed to restore stand structure to an open woodland condition. Results will provide managers with a better understanding of several options for reaching this restoration goal.

2. Methods

2.1. Study sites

This study took place on two of the 13 study sites that comprise the FFS Network: the Green River site (representing the southern Appalachian Mountains) and the Ohio Hills site (representing the central Appalachian Plateau). Each site consists of three replicate blocks, with each of the alternative ecosystem restoration treatments applied to a randomly chosen treatment unit within each block.

The Green River Site is located in Polk County of western North Carolina on the Green River Game Land, which is managed for wildlife habitat, timber, and other resources by the North Carolina Wildlife Resources Commission. The climate of the region is warm continental with mean annual precipitation of 1638 mm (65.5 in.) distributed evenly throughout the year and mean annual temperature of 17.6 °C (64 °F) (Keenan, 1998). The forests of the study area were 80–120 years old, and no indication of past agriculture or recent fire was present, though the historical fire return interval in the area prior to 1940 was approximately 10 years (Harmon, 1982). Forest composition is mixed-oak with pitch pine (*Pinus rigida* Mill.) and Table Mountain pine (*P. pungens* Lamb.) on xeric ridges and white pine (*P. strobus* L.) in moist coves. Chestnut oak (*Quercus prinus* L.), scarlet oak (*Q. coccinea* Muenchh.), white oak (*Q. alba* L.), northern red oak (*Q. rubra* L.), and black oak (*Q. velutina* Lam.) dominated all sites, with other common species including: sourwood (*Oxydendrum arboreum* (L) DC.), red maple, yellow-poplar, mockernut hickory (*C. alba* (L.) Nutt ex Ell.), blackgum (*Nyssa sylvatica* Marsh.), and pitch pine. A dense layer of ericaceous shrubs – mountain laurel (*Kalmia latifolia* L.), rhododendron (*Rhododendron maximum* L. and *R. minus* Michx.), flame azalea (*R. calendulaceum* (Michx) Torr.), and blueberry (*Vaccinium* spp. L.) – is found throughout. While these species are native to the region, they are more common and denser than their historical condition (Brose et al., 2002; Harrod et al., 2000). Dense thickets of ericaceous shrubs create a barrier to regeneration of many vegetative species (Waterman et al., 1995; Turrill et al., 1996) and act as vertical fuels, potentially causing wildfires to reach the tree canopy (Waldrop and Brose, 1999).

Soils at Green River are primarily Evard series (file-loamy, oxidic, mesic Typic Hapludults) with portions of two replications (blocks 1 and 2) of the Cliffield series (loamy-

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skeletal, mixed, mesic Typic Hapludults). These are moderately deep, well drained, mountain upland soils (Keenan, 1998). Elevations range from 366 to 793 m (1200–2600 ft). Blocks 1 and 2 (35°17′N, 82°17′W) were adjacent but separated by Pulliam Creek. Block 3 (35°16′N, 82°18′W) was approximately 2.9 km SE of blocks 1 and 2, across the Green River.

The Ohio Hills FFS site is located on the unglaciated Allegheny Plateau of southern Ohio. The climate of the region is cool temperate with mean annual precipitation of 1024 mm (40.3 in.) distributed evenly over the year and mean annual temperature of 11.3 °C (52 °F) (Sutherland et al., 2003). The forests of the region developed between 1850 and 1900, after the cessation of cutting for the charcoal and iron industries (Sutherland et al., 2003). The current canopy composition differs little from that recorded in the original land surveys of the early 1800s. The most abundant species in the current canopy are white oak, chestnut oak, hickories (*Carya* spp.) and black oak; however, the midstory and understory are now dominated by species that have only in the last few decades become common in this community (e.g. sugar maple (*Acer saccharum* Marsh.), red maple, and yellow-poplar) (Yaussy et al., 2003). Analysis of fire scars in stems of trees that were cut as part of the establishment of the FFS experiment indicated that fires were frequent (return intervals of 8–15 years) from 1875 to 1930. In contrast, few fires occurred after the onset of fire suppression activities in the early 1930s.

The Ohio Hills FFS site is composed of three experimental blocks, with one each in the Raccoon Ecological Management Area, Zaleski State Forest, and Tar Hollow State Forest. Elevations at the three sites range from 207 to 330 m (678–1082 ft).The Raccoon Ecological Management Area block (39°12′N, 82°23′W) and the Zaleski State Forest block (39°21′N, 82°22′W) are both located in Vinton County, OH. These two blocks are underlain by sandstones and shales of Pennsylvanian age (Boerner and Sutherland, 2003). The soils were formed in place from residuum and colluvium, and are dominated by Steinsburg and Gilpin series silt loams (Typic Hapludalfs) (Lemaster and Gilmore, 1993). The Tar Hollow State Forest block (39°20′N, 82°46′W) is located in Ross County, OH. Tar Hollow is underlain primarily by sandstone of Pennsylvanian age, and the soils are dominated by soils of the Shelocta-Brownsville complex sandy loams (Typic Hapludalfs and Typic Dystrochrepts, respectively) (Hamilton et al., 2003). Some of the Tar Hollow ridgetops are capped by loess deposits in which Tar Hollow series silt loams (Typic Hapludalfs) have developed (Hamilton et al., 2003).

2.2. Experimental design

Experiments at both Green River and Ohio Hills were designed as randomized complete blocks with three replicate blocks composed of four factorial treatment units. In the Ohio Hills site, individual treatment units were 19–26 ha (47–64 ac) whereas in the Green River site they were 10–12 ha (25–30 ac) in size. All treatment units were surrounded by buffer zones of approximately 4–10 ha (10–25 ac), and both the treatment unit and its corresponding buffer received the experimental treatment. Buffers were 20 m wide to approximate the height of dominant trees. These treatment units were designed to include all prevailing combinations of elevation, aspect, and soil. However, these conditions varied within experimental units (treatment areas) and could not be separated for analysis. A 50 m × 50 m (164 ft × 164 ft) grid was established in each treatment unit, and 10 sample plots of 0.10 ha were established at randomly selected grid intersections within each treatment unit. The position of each grid point and sample plot was permanently marked and geo-referenced.

Treatments at both Green River and Ohio Hills were selected to alter stand structure in a manner to reduce fuels, improve oak regeneration, and improve wildlife habitat. Restoration to an open woodland habitat may be a means to achieve all goals. Historical descriptions are unavailable that give specific stand parameters such as basal area and cover by species. Rather, we used descriptions of desired conditions for woodlands provided in the Land and Resource Management Plan for a neighboring National Forest (USDA Forest Service, 2004). These plans describe open woodlands as having an open overstory, little or no midstory, and an understory with a mixture of annual and perennial herbs, grasses, and woody regeneration.

Factorial treatments were randomly allocated among treatment units within a site, and all treatment units were sampled through the pretreatment year, 2000 in Ohio Hills and 2001 in Green River. Treatments consisted of prescribed fire, mechanical fuel reduction, the combination of prescribed fire and mechanical treatment, and an untreated control. In Green River, the mechanical treatment involved creating a vertical fuel break by chainsaw felling all tree stems >1.8 m (6 ft) tall and <10.2 cm (4 in.) diameter at breast height (dbh) as well as all mountain laurel and rhododendron stems, regardless of size. Previous work by Waldrop and Brose (1999) and Waldrop et al. (2007) showed that ericaceous shrubs are widespread throughout the southern Appalachian Mountains and that fire intensity can become high where these shrubs are dense. In Ohio Hills, the mechanical treatment was a commercial thinning from below to a basal area comparable to that present prior to Euro-American settlement (approximately 14 m^2/ha (60 ft^2/ac)). Previous research showed that 60 ft^2 basal area in a mature stand of this forest type, closely approximates the conditions that provide optimal growth of residual trees and the proper light environment for the growth of oak seedlings into saplings (Gingrich, 1967, McQuattie et al., 2005). Thinning was conducted by contract crews who felled trees by chainsaw and yarded with rubber-tired skidders. All slash generated by the mechanical treatment was left on site in Green River; in Ohio Hills merchantable stems were removed for sale but all other slash was left on site.

Mechanical treatments were accomplished between September 2000 and April 2001 in Ohio and between December 2001 and February 2002 at Green River. The prescribed fires were applied during March–April 2001 at Ohio Hills and March 2003 at Green River. A second fire was conducted at both sites in burn-only and mechanical + burn treatment units (2005 Ohio Hills, 2006 Green River). The Ohio fires consumed unconsolidated leaf litter and fine woody fuels while leaving the

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majority of the coarse woody fuels only charred. Flame lengths were generally less than 1 m (3 ft) for the 2001 fires, but higher intensities were intentionally created in the 2005 fires with flame lengths reaching 1–2 m (3–6 ft) and 4–5 m (13–16 ft) in some areas. At Green River, the objectives of prescribed burning were to remove the shrub layer and create a few snags for habitat. During the first fire, flame lengths of 1–2 m (3–6 ft) occurred throughout all burn units but reached up to 5 m (16 ft) in localized spots. Loads of fine woody fuels in mechanical + burn sites were essentially double that of burn-only sites due to felling of the shrub layer. Temperatures measured with thermocouples placed 30 cm (12 in.) above ground averaged 180 °C (356 °F) during 2003 and 155 °C (311 °F) during 2006 in burn-only sites. Fires in mechanical + burn sites were considerably hotter with mean temperatures of 370 °C (698 °F) in 2003 and 222 °C (432°F) in 2006. Additional details of fire behavior are given by Iverson and Hutchinson (2002) for the Ohio Hills site and Tomcho (2004) for the Green River site.

2.3. Sampling and analysis

Vegetation data were collected on 10 sample plots established prior to treatment. Each sample plot was 0.1 ha (0.25 ac) in size and located at randomly-selected grid points throughout each treatment unit. Each plot was 50 m × 20 m (164 ft × 66 ft) in size and divided into 10 subplots, each 10 m × 10 m (33 ft × 33 ft) in size. In Ohio Hills, measurements of all vegetation variables were taken prior to treatment and at 1 and 4 years following treatment. An additional measurement of overstory trees was taken 6 years after treatment (1 year after the second burn). In Green River, all vegetation measurements were made prior to treatment and then 1 and 3 years post treatment. Another set of measurements was made 5 years after initial treatment which was 1 year after the second burn.

All Trees 10 cm dbh (4 in.) or larger were measured in all 10 subplots at Ohio Hills. Five subplots were measured at Green River because stem density was considered too high to complete all measurements in the field season. For each tree, the tree number, species, dbh, and status were recorded. Status included: standing live or standing dead during pretreatment and post-treatment samples. After treatment, trees were also recorded as dead and down or harvested but those trees were not measured for dbh. Overstory mortality was computed as the total basal area of trees whose status changed from live to dead during each sample year in all 0.1-ha (0.25 ac) vegetation plots ($n = 30$ plots per treatment).

Saplings (trees >1.4 m tall (4.5 ft) and <10 cm (4 in.) dbh) and shrubs were measured on five 10 m × 10 m subplots. Saplings were recorded by species, status, and dbh class. Status included live (unaffected by treatment), topkilled (aboveground stem dead but sprouts present), dead, or harvested. Dbh classes included <3 cm (1.2 in.), 3–6 cm (1.2–2.4 in.), and >6 cm (2.4 in.). Ocular estimates of the percentage of area covered by the crowns of each shrub species were also recorded within five subplots. Sapling and shrub data were combined into broad species groups for analysis. Dominant species or species of special interest were selected which included all oaks, red maple, and yellow-poplar while shrubs included mountain laurel and rhododendron for Green River and *Rubus* (*Rubus* spp. L.), and *Smilax* (*Smilax* spp. L) at Ohio Hills. Mean percent cover values were evaluated for each species or species group.

A total of 20, 1 m^2 (10.8 ft^2) quadrats were established in each vegetation sample plot to measure the herbaceous layer. Quadrats were located at the upper-right and lower-left corner of each 10 m × 10 m subplot. All trees <1.4 m (4.5 ft) tall were recorded by height class category including <10 cm (4 in.), 10–50 cm (4–20 in.), and 50–139 cm (20–55 in.). Shrubs (<1.4 m tall) and all herbaceous species were recorded by species and cover class. Cover classes included <1%, 1–10%, 11–25%, 26–50%, 51–75%, and >75%. All species in the groundcover vegetation were classified into general life form categories (forbs, grasses, shrubs, and trees) at both study sites for analysis, using mean percent cover values for each plot. Additionally, the tree cohort of the groundcover vegetation was subjected to further analysis, separated into the same species groups used in the overstory mortality analysis.

Data analyses were conducted separately for the Green River and Ohio Hills sites. To analyze treatment effects on vegetation, we used repeated measures ANOVA, with treatment and year modeled as fixed effects and block as a random effect, to test for differences within the overstory mortality, sapling, shrub, and groundcover at both sites. To account for differences among years, we interpreted significant treatment and (or) treatment × year interactions ($\alpha = 0.05$), as evidence of treatment effects and made post-hoc comparisons using Tukey's multiple comparison procedure. As much of these data did not meet the assumption of normality, it was necessary to use data transformations to normalize the distributions. Logarithmic, square root, and arcsin transformations were used in these analyses; however, all reported means were calculated using the non-transformed data.

3. Results

3.1. Overstory

Basal area of live trees on the Green River site varied from 23.8 to 27.3 m^2/ha (104–119 ft^2/ac) prior to treatment but the differences were not significant (Fig. 1a). After one growing season, basal area had not changed significantly from pretreatment levels except in plots treated with the mechanical + burn combination. In those plots, basal area declined from 23.8 to 21.0 m^2/ha (104–91.5 ft^2/ac) due to mortality after hot fires. Burn-only and mechanical-only plots continued to have no significant differences from control plots at measurements during years 3 and 5. However, basal area continued to decline significantly between sample years in the mechanical + burn plots, leaving only 16.5 m^2/ha (72 ft^2/ac) of live trees after 5 years. An analysis of mortality (Fig. 2a) showed that the basal area of trees that died during the first year after treatment was significantly higher in burn-only and mechanical + burn plots than in those plots not treated with fire. Some mortality occurred in all treatment units between

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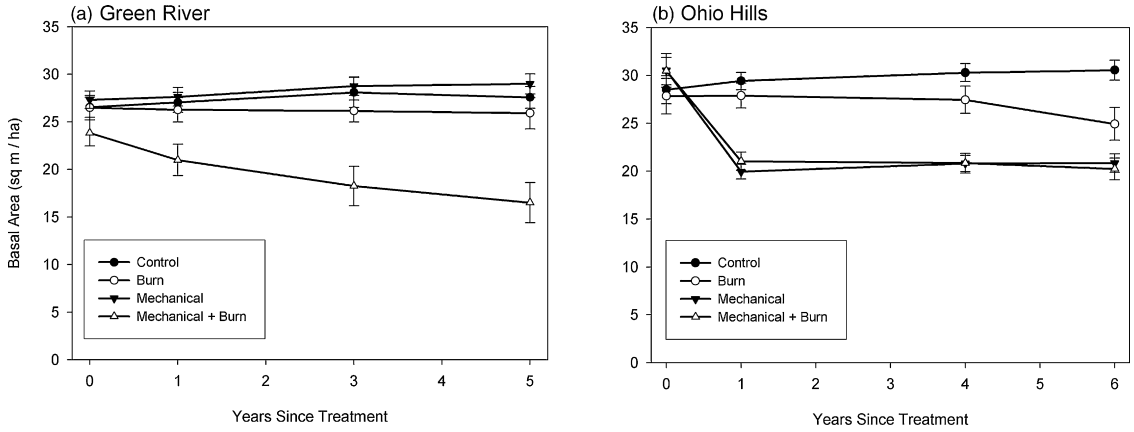
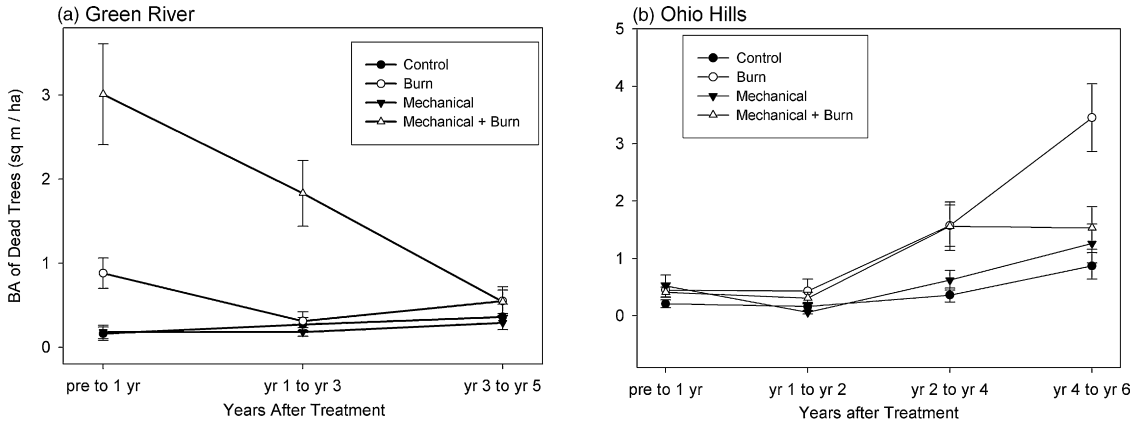


Basal Area

	Treatment	Pretreatment	p	Yr 1	p	Yr 3	p	Yr 5
Green River	Control	26.5	0.2484	27.0	0.0902	28.1	0.1849	27.6
	Burn	26.5	0.5987	26.3	0.8358	26.1	0.5496	25.9
	Mechanical	27.3	0.4852	27.6	0.0645	28.8	0.5782	29.0
	Mech + Burn	23.8	0.0001	21.0	0.0001	12.3	0.0001	16.5
		Pretreatment	p	Yr 1	p	Yr 4	p	Yr 6
Ohio Hills	Control	28.5	0.6261	29.4	0.0106	30.4	0.6572	30.6
	Burn	27.9	0.1042	27.9	0.2249	27.5	0.0001	24.9
	Mechanical	30.5	0.0001	20.0	0.0220	20.8	0.9203	20.9
	Mech + Burn	30.5	0.0001	21.0	0.5854	20.8	0.7247	20.3

P values indicate differences between means in successive years.

Fig. 1. Change in basal area (m^2/ha) by treatment and year for the Green River (NC) (a) and Ohio Hills (b) sites of the Fire and Fire Surrogate Study.



Basal Area

	Treatment	Pretreatment - 1yr post	p	Yr 1 - Yr 3	p	Yr 3 - Yr 5		
Green River	Control	0.16	0.1947	0.27	0.834	0.36		
	Burn	0.88	0.0005	0.31	0.1527	0.55		
	Mechanical	0.18	0.4716	0.18	0.6048	0.29		
	Mech + Burn	3.01	0.0141	1.83	0.0001	0.54		
		Pretreatment - 1yr post	p	Yr 1 - Yr 2	p	Yr 2 - Yr 4	p	Yr 4 - Yr 6
Ohio Hills	Control	0.21	0.0073	0.16	0.1925	0.36	0.1177	0.87
	Burn	0.45	0.0128	0.43	0.0001	1.57	0.0001	3.45
	Mechanical	0.52	0.0363	0.06	0.0031	0.62	0.2277	1.26
	Mech + Burn	0.41	0.0159	0.31	0.0001	1.56	0.7607	1.53

P values indicate differences between means in successive years.

Fig. 2. Basal area (m^2/ha) of trees that died since the last sample at the Green River (NC) (a) and Ohio Hills (b) sites of the Fire and Fire Surrogate Study.

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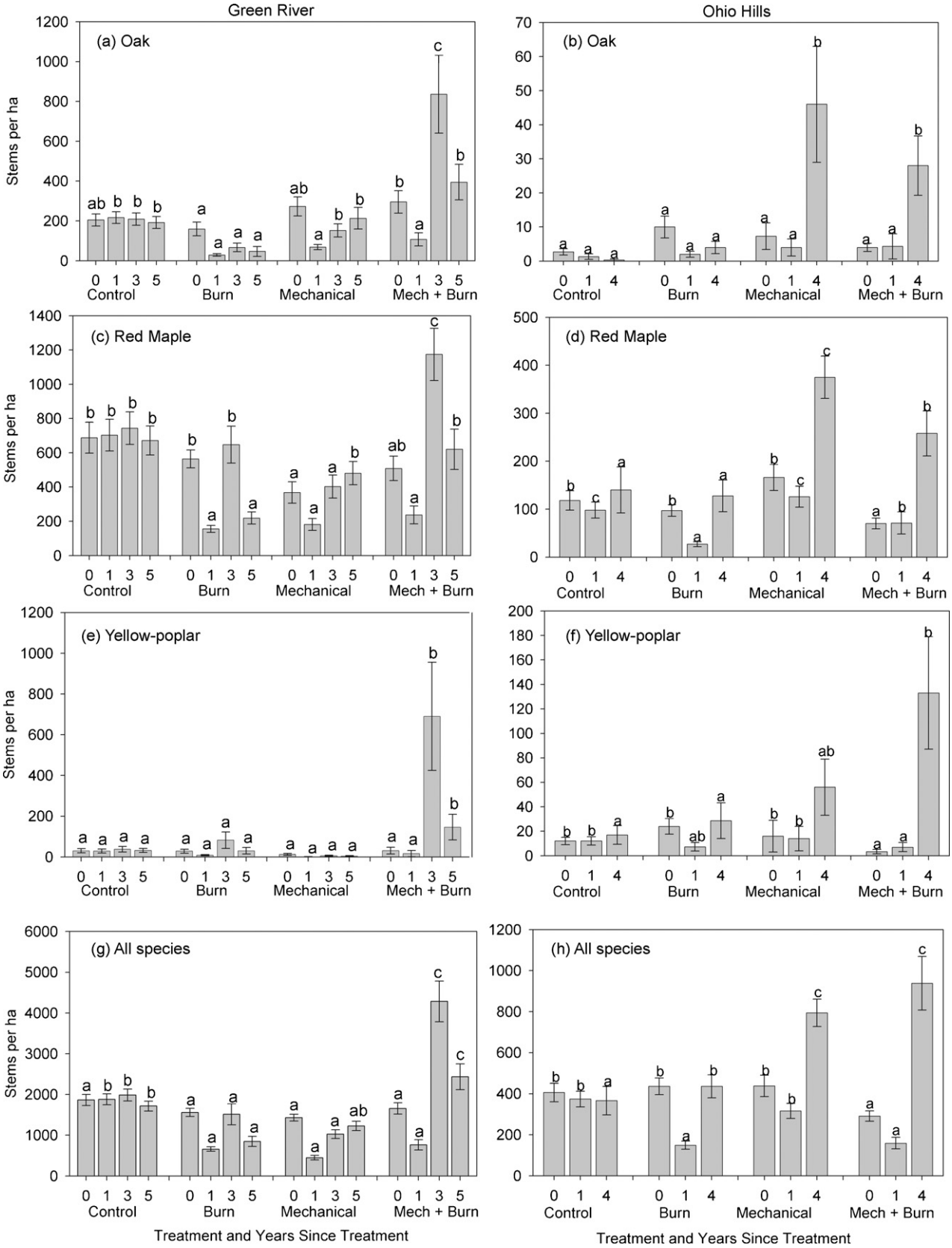

Fig. 3. Density of hardwood saplings (stems/ha) by treatment and year for select species and species groups at the Green River (NC) and Ohio Hills sites of the National Fire and Fire Surrogate Study. Error bars indicate differences among years within a treatment. Letters indicate differences among treatments within a year.

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each sample period but there was significantly more mortality in the mechanical + burn plots for 3 years following burning. At the end of 5 years, the only treatment that continued to have significant amounts of mortality was the mechanical + burn treatment. Species composition of the overstory was unaffected by treatment with mortality consistent among all species.

In Ohio Hills, the overstory responded differently than at Green River, primarily due to the difference in mechanical treatments (commercial thinning instead of understory cutting). Plots randomly selected for mechanical treatment had significantly higher basal area of live trees prior to treatment (30.5 m^2/ha (133 ft^2/ac)) than did plots selected for burn-only (27.9 m^2/ha (122 ft^2/ac)) or no treatment (28.5 m^2/

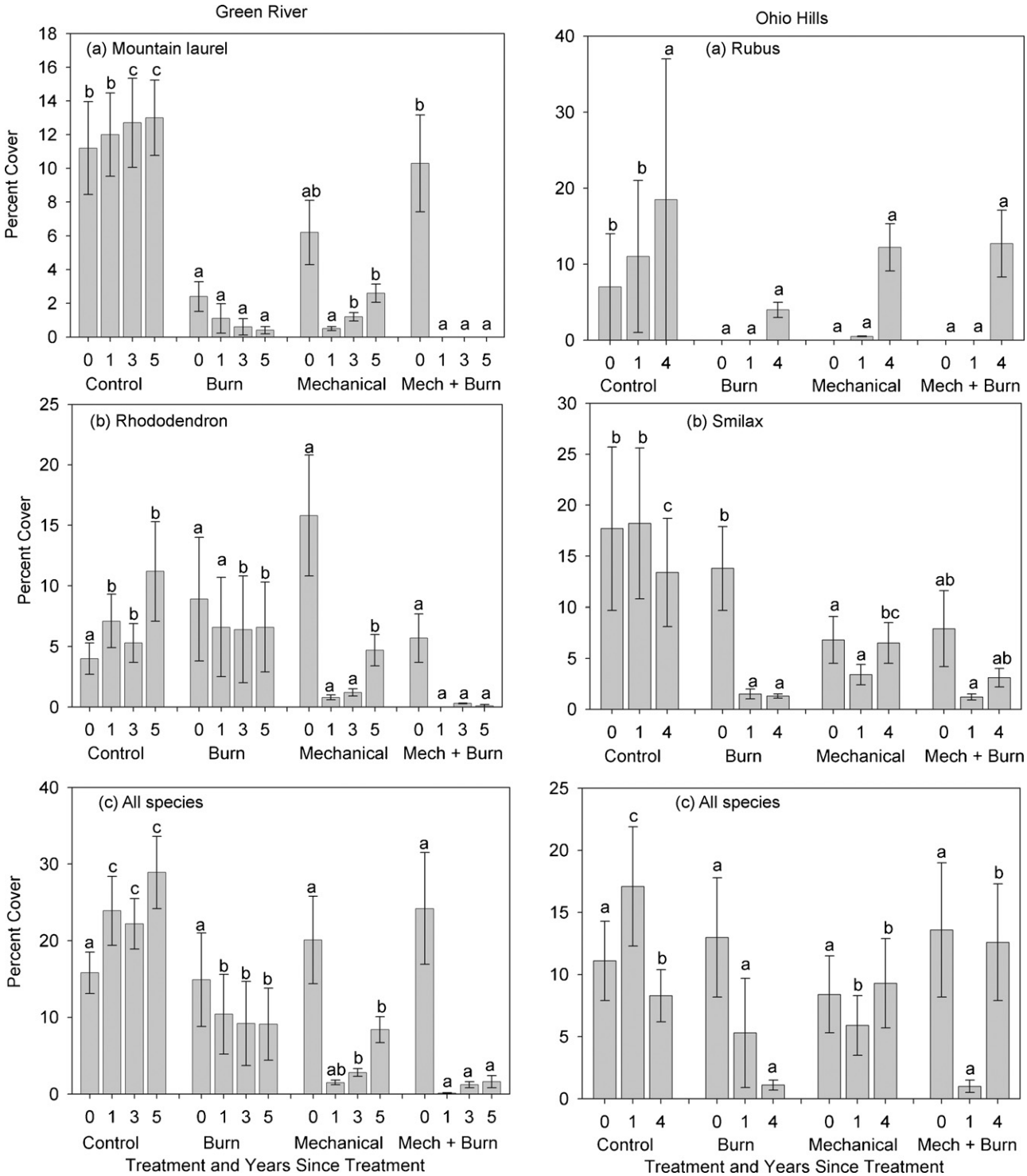

Fig. 4. Percent cover of shrubs by treatment and year for select species and species groups at the Green River (NC) and Ohio Hills sites of the National Fire and Fire Surrogate Study. Error bars indicate differences among years within a treatment. Letters indicate differences among treatments within a year.

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ha (124 ft^2/ac)) (Fig. 1b). Commercial thinning operations did not achieve the target basal area of 14 m^2/ha (60 ft^2/ac), leaving 20.0 and 20.1 m^2/ha (87.2 and 87.6 ft^2/ac) in the mechanical-only and mechanical + burn plots, respectively. Basal area in both treatment units remained about the same throughout the remainder of the 6-year measurement period. Basal area of live trees in burn-only treatment units was not significantly different than in untreated control plots the first year after burning. However, basal area increased in control plots over time as trees grew but decreased over time in burn-only plots as trees died. The reduction of live basal area in burn-only plots was significant between years 4 and 6. Some mortality occurred in all treatment units the first year after treatment but the amounts were small and not significantly different (Fig. 2b). Between 2 and 4 years after treatment, mortality increased in the areas treated with fire to levels significantly higher than in the controls or mechanical-only treatments. Mortality remained significantly higher in burn-only plots through year 6. Species composition of the overstory was unaffected by treatment with mortality consistent among all species.

3.2. Midstory saplings and shrubs

Numbers of sapling-sized trees of all species groups tended to be significantly reduced 1 year after burning at both Green River and Ohio Hills (Fig. 3). Sapling numbers increased over time at Ohio Hills, sometimes exceeding pretreatment densities. At Green River, however, there was a reduction in numbers at year 5 because this was the first growing season after the second burn. Chainsaw felling at Green River reduced sapling density immediately after treatment but there were no significant differences in sapling numbers for red maple and oaks by years 3 and 5, respectively. The mechanical treatment at Ohio Hills had little impact on sapling numbers the first year after treatment. Sapling numbers increased significantly by year 4 as large numbers of small trees grew into the sapling size class (Fig. 3h). The mechanical + burn treatment at Green River showed similar results to the mechanical treatments at Ohio Hills with large increases in sapling density as trees grew into this size category by year 3 (Fig. 3g).

Recruitment of oaks is a desirable outcome for both timber and wildlife objectives. Oak sapling density was greatly

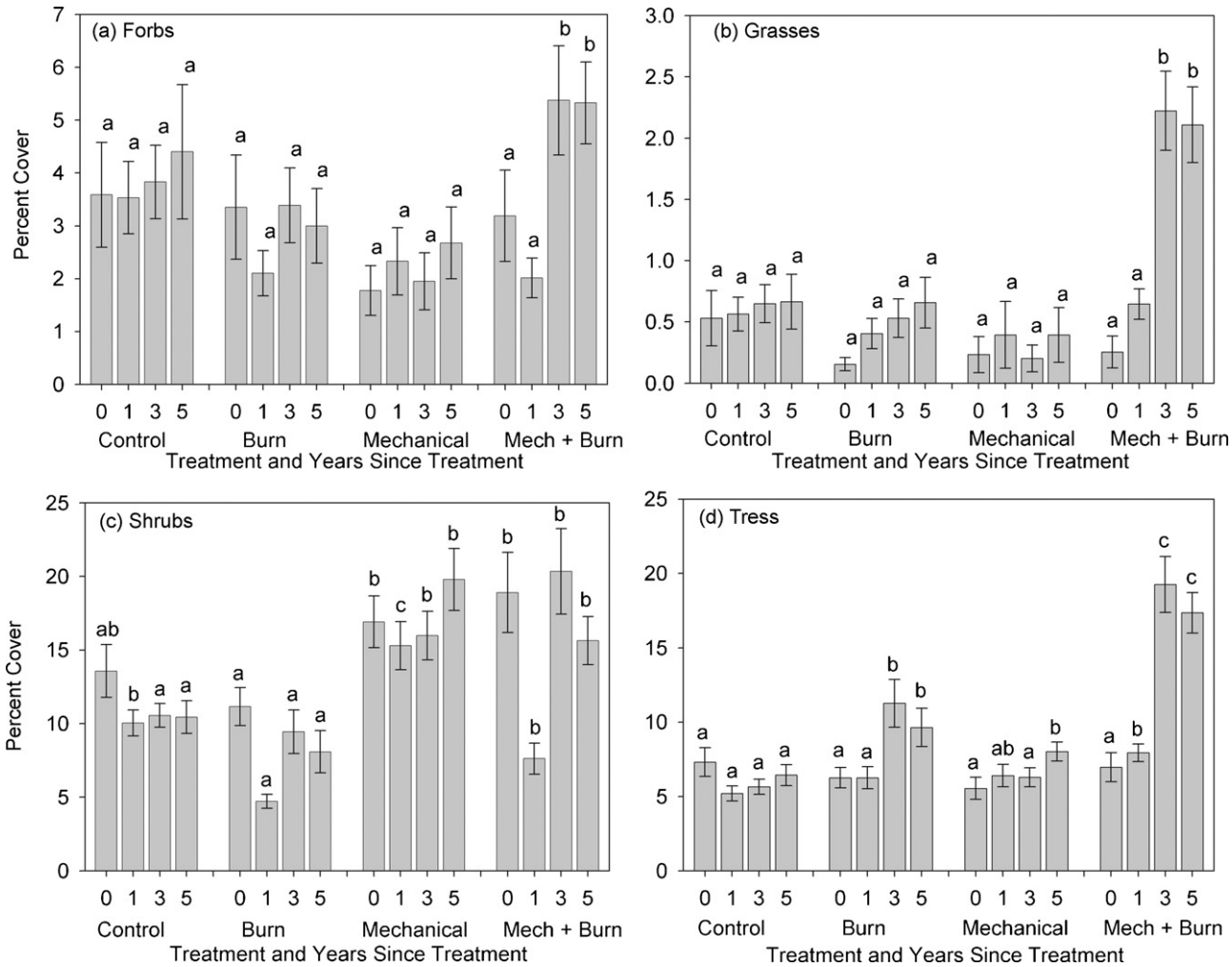

Fig. 5. Percent cover of ground layer vegetation by treatment and year for select species groups at the Green River (NC) site of the National Fire and Fire Surrogate Study. Error bars indicate differences among years within a treatment. Letters indicate differences among treatments within a year.

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increased by the mechanical treatment at Ohio Hills and the mechanical + burn treatment at both study sites (Fig. 3a, b). However, heavy competitors such as yellow-poplar and red maple also increased in number by as many as 1.5 times the number of oaks at Green River (Fig. 3c and e) and 6 times their number at Ohio Hills (Fig. 3d and f). No treatment was successful at increasing oak sapling density without an equal or greater increase in the density of red maple or yellow-poplar.

Cover of the shrub layer at Green River was generally unaffected by the burn-only treatment (Fig. 4). The mechanical treatment, both with and without burning, was more effective at removing this vertical fuel layer than was burning alone, primarily because burning did little to remove the rhododendrons (Fig. 4b) which grew in moist areas that did not burn. Mountain laurel cover was significantly reduced the year following the mechanical-only and mechanical + burn treatments (Fig. 4a). Burning again after 3 years essentially eliminated this species from the shrub layer from burn only and mechanical + burn plots as opposed to the mechanical-only plots where mountain laurel is growing tall enough to re-enter this layer. The predominant shrubs at Ohio Hills are different species from those at Green River, consisting of *Rubus* and *Smilax* species. *Rubus* was essentially absent from plots before mechanical or burning treatments (Fig. 4a) but increased significantly by year 4 as these species responded to canopy opening and grew tall enough to reach the shrub layer. *Smilax* (Fig. 4b) was reduced by all active treatments during the first year but was beginning to return to pretreatment levels by year 4 in mechanical and mechanical + burn treatment areas.

3.3. Forest floor vegetation

The vegetation less than 1.4 m (4.5 ft) tall was dynamic at both Green River (Fig. 5) and Ohio Hills (Fig. 6), changing each year. At Green River, forb cover did not change following burning but increased significantly over pretreatment values by year 3 in mechanical + burn areas (Fig. 5a). Grasses showed significant increases the first year after the burn-only treatment and at years 1 and 3 for the mechanical + burn treatment units (Fig. 5b). Grass cover was significantly higher in the mechanical + burn plots after year 3. Shrub cover was reduced immediately after the first burn at Green River but returned to pre-burn levels by year 3. The second burn reduced shrub cover again but the difference was significant for only the

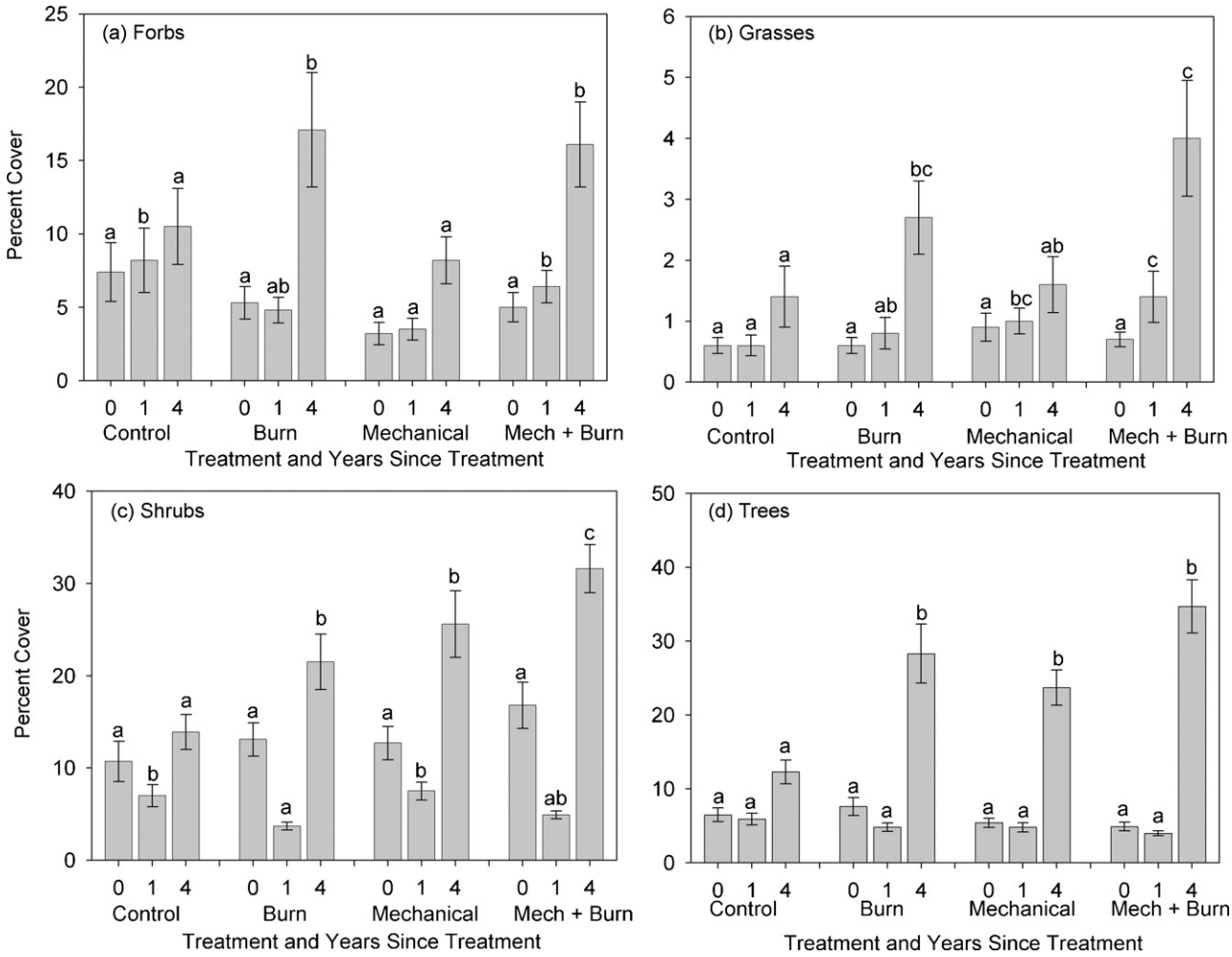

Fig. 6. Percent cover of ground layer vegetation by treatment and year for select species groups at the Ohio Hills site of the National Fire and Fire Surrogate Study. Error bars indicate differences among years within a treatment. Letters indicate differences among treatments within a year.

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mechanical + burn treatment. Tree cover was not affected by any treatment during the first year at Green River (Fig. 5d) but significantly increased by year 3 and remained high after the second burn in burn only and mechanical + burn plots.

At Ohio Hills, herbaceous vegetation (Fig. 6a and b) was unaffected the first year after treatment with the exception of a significant increase in grasses with the mechanical + burn treatment. Large increases in forb and grass cover occurred between years 1 and 4 in all active treatment units. Grasses increased significantly in burn only and mechanical + burn plots. Grass cover was significantly higher in mechanical + burn plots after 4 years than in all other treatment areas except in burn only plots. Cover of woody vegetation at Ohio Hills (Fig. 6c and d) decreased or stayed the same 1 year after treatment in mechanical and burned plots. By year 4, however, woody cover was much higher in all treated areas as sprouts from trees and shrubs became established.

Of special concern among forest floor vegetation is the regeneration of desirable (oak) and undesirable (red maple and yellow-poplar) tree species. Treatment impacts varied among oaks, red maple, and yellow-poplar at both Green River and Ohio Hills (Fig. 7). At Green River, the oaks (Fig. 7a) showed little response to any treatment during the first year after treatment but increased significantly in number between years 1 and 3 in burn only and mechanical + burn plots. A decrease was observed in year 5 after the second burn but the difference was

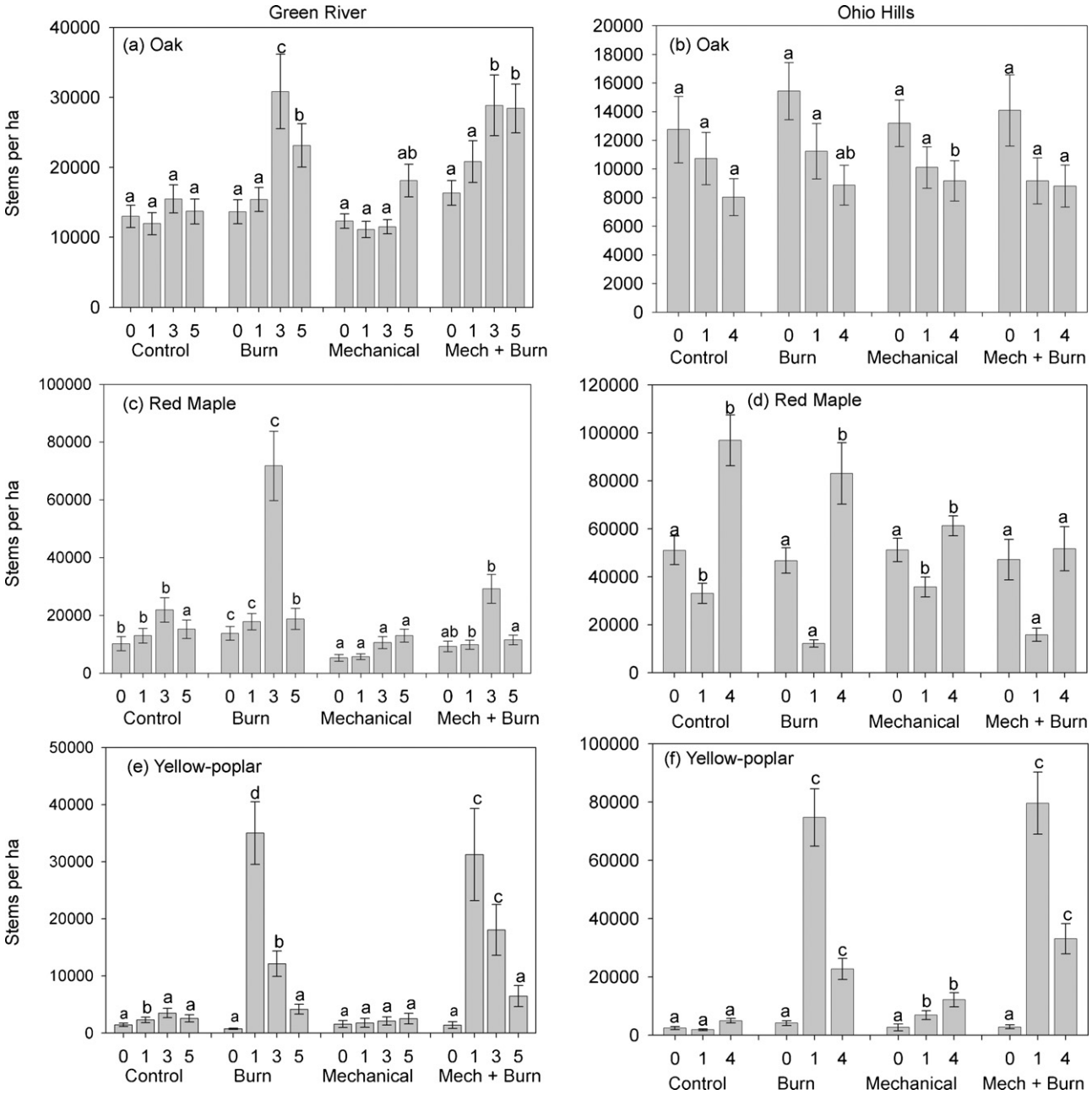

Fig. 7. Density (stems/ha) of tree regeneration by treatment and year for select species and species groups at the Green River (NC) and Ohio Hills sites of the National Fire and Fire Surrogate Study. Error bars indicate differences among years within a treatment. Letters indicate differences among treatments within a year.

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not significant. The mechanical-only treatment had little initial impact on oak regeneration at Green River but a significant increase was observed between years 3 and 5. Oak numbers decreased at Ohio Hills (Fig. 7b) in all treatment units during the first year after treatment, although the difference was not significant in the mechanical-only treatment unit. No changes occurred between years 1 and 4.

Competitors of oak tended to follow the same patterns at Green River and Ohio Hills. Red maple showed little response to treatment during the first year at Green River but had significant decreases in number for all treatments, including the control, at Ohio Hills (Fig. 7c and d). Burning, with and without mechanical treatment, significantly increased red maple numbers at years 3 (Green River) or 4 (Ohio Hills) but the second burn at Green River reduced numbers to pretreatment levels. Yellow-poplar increased over time in the mechanical-only plots at Ohio Hills. However, this response was small in comparison to the large increase in numbers of yellow-poplar seedlings observed the first year after burning at both sites. These numbers decreased by the third measurement at both sites and even more after the second burn at Green River.

4. Discussion

Restoration of hardwood ecosystems of the southern Appalachian Mountains and central Appalachian region is challenging because they have been protected from fire for decades, resulting in dramatic changes in stand structure. Treatments selected for the two hardwood sites of the FFS study provide a range of options for restoration which included commercial thinning at the Ohio Hills site, chainsaw felling of saplings and shrubs at the Green River site, winter prescribed burning at both sites, and a combination of mechanical and burning treatments at both sites. Each treatment was designed to restore open woodland conditions by altering stand structure (mechanical treatments), re-introducing an ecosystem process (fire), or both. However, none of the treatments at Green River or Ohio Hills was entirely successful at recreating this historical stand structure but each began the process of restoration.

Winter prescribed burns were conducted twice at Ohio Hills and Green River during the study period. The burn-only treatment at both sites created some overstory mortality but stand basal area was reduced only slightly as surviving trees continued to grow. Mortality was continuing at Ohio Hills and may eventually result in more open stands. This result was unexpected as we assumed that most mortality would occur during the first year after treatment. Hardwoods exhibited a delayed response to fire suggesting that observations and conclusions drawn 1 year after burning may be premature. After 6 years, the mechanical treatments were the most effective at opening the overstory but continued mortality in the burn-only plots may lower basal area to levels equal to or lower than that of the mechanical treatments. Although the cause for delayed mortality is uncertain, a preliminary analysis indicates that a combination of factors, such as fire temperature, tree size and species, and tree vigor is involved (Yaussy and Waldrop, 2008).

Fire reduced the sapling and shrub layer at both sites. This is especially important at Green River where dense mountain laurel can act as a vertical fuel. The sapling/shrub layer was beginning to grow back at Ohio Hills, particularly where thinning opened the canopy and allowed greater amounts of sunlight to reach the forest floor. Similar results occurred in the mechanical + burn plots at Green River where heavy mortality created canopy openings. These results suggest that repeated treatments, whether mechanical, fire, or both are needed to reduce fuels and reach restoration objectives. Forbs and grasses showed increases in response to burning at both sites, with the mechanical + burn plots containing the greatest abundance. Tree regeneration was abundant at both sites including oaks, red maple, and yellow-poplar. A single burn at Ohio Hills decreased oak regeneration but increased the density of its competitors. At Green River, two burns seemed to favor oak regeneration by severely reducing density of red maple and yellow-poplar. This result agrees with the results of Brose and Van Lear (1998) who emphasized the need for prescribed burning after yellow-poplar seedlings become established. Oaks were 4–6 times more numerous after the second burn at Green River than were seedlings of yellow-poplar. The burn-only treatment changed stand structure by reducing the sapling/shrub layer but it did little to thin the overstory.

The mechanical-only treatment differed in design at the two study sites. At Ohio Hills, the commercial thinning from below quickly changed stand structure by removing overstory trees. However, the residual overstory was more dense than anticipated (20 m^2/ha (87.2 ft^2/ac) instead of 14 m^2/ha (60 ft^2 /ac). After cutting, the midstory became denser as sprouts from cut stems and shrubs grew rapidly in the canopy openings. Cover of forest floor vegetation increased as woody species sprouted but oak regeneration was reduced by its competitors. Forb and grass cover was increased by greater light availability, but more intense levels of harvesting may be required to elicit significant changes in herbaceous abundance (Zenner et al., 2006). The mechanical treatment at Green River essentially removed the entire sapling/shrub layer with chainsaw felling which had no impact on overstory density. Cut trees and shrubs sprouted and the regeneration is growing back into this understory/midstory layer. Herbaceous vegetation on the forest floor was unaffected by this treatment but there was a slight increase in oak regeneration with no increase in its competitors. Mechanical treatments at Ohio Hills and Green River quickly altered stand structure by removing all or a portion of one canopy layer. However, these one-time treatments will eventually cause the midstory to become denser if they are not repeated.

The combination of mechanical treatment and burning produced the greatest changes in stand structure, especially at Green River. Overstory basal area at Ohio Hills was reduced from 30.5 m^2/ha (133 ft^2/ac) to 21.0 m^2/ha (91.5 ft^2/ac) by thinning and some mortality occurred after burning. However, basal area remained higher than the target of 14 m^2/ha (60 ft^2/ac). Even though the mechanical + burn treatment produced more mortality than the mechanical-only treatment, the residual basal area remained the same, suggesting that additional growth

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in the mechanical + burn plots offset the loss from mortality. At Green River, the mechanical treatment did not involve commercial thinning, but hot fires resulting from cutting shrubs produced the most open stands of any treatment at either site (16.5 m^2/ha (72 ft^2/ac)). As with other treatments that opened the canopy, saplings became dense over time. Shrubs were essentially removed by this treatment at Green River after the second burn but may grow back with time. Forest floor vegetation included an increase in woody species at both sites and an increase in grasses at Green River. Regenerating oaks increased with this treatment at Green River but decreased at Ohio Hills. The combination of mechanical and burning treatments was the most effective for quickly changing stand structure and promoting oak regeneration. However, all vegetative layers remained too dense (with the exception of the overstory in mechanical + burn treatment units at Green River) to meet the objective of creating an open woodland community.

All treatments at both Green River and Ohio Hills effectively altered stand structure but none created stands with open canopies, absent midstory, and diverse understory vegetation. Understory vegetation regenerates and grows quickly in eastern hardwood ecosystems. While these two studies provide much information on vegetative response to restoration treatments, they do not provide definitive results to meet our restoration goals. Repeated treatments with fire or mechanical means are needed over a period of time to replicate historical structure that was maintained by frequent disturbance.

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