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The effect of prescribed fire on gap fraction in an oak forest understory on the Cumberland Plateau[1,2]

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CHIANG, J-M., M. A. ARTHUR, AND B. A. BLANKENSHIP (Department of Forestry, University of Kentucky, Lexington, KY 40546-0073). The effect of prescribed fire on gap fraction in an oak forest understory on the Cumberland Plateau. J. Torrey Bot. Soc. 132: 432–441. 2005.—Excessive shade in the understory has been widely cited as the most important factor causing poor oak regeneration in eastern deciduous forests. We examined the effect of single and multiple fires on forest stand structure and the consequent impacts on the gap fraction measured in the understory. Differences in midstory stem density (stems 2–15 cm diameter at breast height; DBH) before and after prescribed burning were highly correlated with fire frequency ($R^2 = 0.86$, $P < 0.01$). On average, each additional burn reduced midstory stem density by ~550 stems per hectare. Hemispherical photography showed an increase of 3.8 % in understory gap fraction in the first growing season after burning. This increase in gap fraction, which was likely caused by the thinning of the midstory by prescribed burning, was quickly reduced in the next year. Decreases in gap fraction after the first year post-fire, which indicated progressive canopy closure, cannot be explained by the relatively stable midstory stem density in subsequent years after fire. Rather, the decreases in gap fraction after fire coincided with a rapid increase in stem density in the shrub stratum (> 50 cm in height and < 2 cm DBH) of more than two thousand stems/ha/year. The rapid flush of stump sprouts in the shrub stratum was the primary cause of the decrease in the understory gap fraction. Land managers whose goal is to improve oak regeneration by increasing the understory light environment through the use of prescribed burning will need to control the flush of stump sprouts to maintain the effectiveness of burning in increasing light availability. Multiple fires of the intensity used in this study failed to permanently reduce sprouts.

Key words: light, forest structure, oak regeneration, *Quercus*, *Acer rubrum*, hemispherical photography

Oak species (*Quercus* spp.) have dominated much of the central hardwood forest for at least 6,000 years (Watts 1979, Delcourt and Delcourt 1987, Delcourt et al. 1998). However, in the past several decades, declining success of oaks has been attributed to a variety of possible causes, including poor seed production, acorn predation and consumption, damage to seedlings by animals, selective logging of oaks, disease, climate change, and excessive shade and competition (Abrams 1992, Lorimer 1993). Among the many factors that have been cited in causing poor oak regeneration, excessive shade from species with greater shade tolerance, such as red maple (*Acer rubrum* L.), is considered a key factor (Gottschalk 1994, Lorimer et al. 1994, Barnes and Van Lear 1998). This is supported by the fact that oaks are physiologically poorly adapted to a low light environment compared to their shade tolerant competitors (Abrams 1992, Lorimer 1993). Survival and growth of oaks are largely dependent on understory light levels that are higher than those achieved under a closed canopy (Loach 1970), although there is evidence that increased light may not favor oaks over red maple because of the latter species greater plasticity in responding to a changing light environment (Gottschalk 1994).

The dominance of oak species in North America has been closely linked to recurring fires (Abrams 1992, Delcourt et al. 1998, Shumway et al. 2001). Prehistoric Native Americans and post-settlement Euro-Americans used fires for various purposes (Pyne 1982, Lorimer 1993, Delcourt et al. 1998) and recurrent fires, primarily resulting from human activities, were once an important force in arresting succession and maintaining low stand density in the eastern deciduous forest (Abrams 1992). Fire histories developed from tree ring records have demonstrated a fire return interval in eastern hardwood

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forests ranging from 2.8 to 14 years (Cutter and Guyette 1994, Sutherland 1997, Shumway et al. 2001), with longer intervals (and active fire suppression activities) beginning in the 1930s which coincide strongly with a reduction in oak regeneration and a proliferation of fire-sensitive species such as red maple (Shumway et al. 2001) and white pine (Wehner 1991). Simultaneously, these forests were recovering from heavy logging and the aftermath of the chestnut blight (Keever 1953, McCormick and Platt 1980), setting in motion processes that also have almost certainly contributed to the changing structure and composition of these forests.

Focusing on the apparent relationship between fire suppression and poor oak regeneration, managers are increasingly using fire as a tool to regenerate oak species, despite a lack of data demonstrating the effectiveness of prescribed fire alone (without forest thinning or herbicide treatment) to alter stand structure and increase light availability to the seedling stratum. Although it can be argued that the understory light environment cannot be sufficiently altered without partial cutting, the effect of multiple prescribed fires on the light environment has been neither specifically documented nor sufficiently examined. Studies of prescribed fire in the southeastern US have shown that repeated late-winter fire enhances the proliferation of hardwood stem density in the understory, many of which stems are of predominantly sprout origin (Thor and Nichols 1974, Waldrop and Lloyd 1991). However, the effects of multiple prescribed fires on stand structure and light environment have rarely been documented in this forest region (Robison and McCarthy 1999) and have not, to our knowledge, been previously examined on the Cumberland Plateau.

We investigated the effects of single and multiple prescribed fires on the understory light environment in upland oak forests on the Cumberland Plateau in eastern Kentucky. The objectives of this study were to examine single and multiple (two to three) prescribed fires to determine: (1) the effects of prescribed fire on forest stand structure, (2) the interrelationships between prescribed fire, stand structure, and understory light environment, and (3) the persistence of changes in the understory light environment after burning.

Methods. SITE DESCRIPTION. The study was conducted on Klaber (37° 57′ N, 83° 37′ W) and Whittleton ridges (37° 46′ N, 83° 39′ W) in the Red River Gorge Geological Area of Daniel Boone National Forest of eastern Kentucky. This area is located in the Cliff Section of the Cumberland Plateau (Braun 1950). Annual precipitation at Heidelberg, in eastern Kentucky, is 1134 mm with the driest month in October (52 mm) and wettest in July (134 mm). Monthly mean temperatures in January and July are 2.2 °C and 24.2 °C, respectively, with mean annual temperature of 13.3 °C (Hill 1976). The canopy species (defined as stems > 15 cm DBH) in the study areas are mostly composed of oak species (*Quercus coccinea* Muenchh., *Q. prinus* L., *Q. alba* L., *Q. velutina* Lam.) with some hard pines (*Pinus rigida* Mill., *P. virginiana* Mill., *P. echinata* Mill.) scattered throughout. The midstory (stems with DBH between 2 and 15 cm) is mostly composed of blackgum (*Nyssa sylvatica* Marsh.), red maple, and sourwood (*Oxydendrum arboreum* [L.] DC.). The shrub stratum (> 50 cm in height and < 2 cm DBH) is mostly composed of red maple, blackgum, eastern white pine (*P. strobus* L.), and sassafras (*Sassafras albidum* [Nutt.] Nees) (M. A. Arthur, unpublished data). Botanical nomenclature follows Gleason and Cronquist (1991). Oaks are not important in either the midstory or shrub stratum (less than 6% in relative density), although oak seedling density in the herbaceous stratum (stems <50 cm in height) was approximately 8000 seedlings/ha (Kuddes-Fischer and Arthur 2002).

Three prescribed fire treatment sites (2 burned and 1 reference) were established on each of Klaber and Whittleton ridges for long-term monitoring of the effects of burning on oak regeneration and stand structure. Although originally designed in 1995 as a replicated experiment with two burn treatments and a reference on each of three ridges, weather-related constraints on prescribed burning reduced the design to burn treatments conducted in different years on two ridges. The sizes of the treatment sites were 30 to 40 ha each. On Klaber Ridge, one treatment was burned three times, in the late winter of 1995, 1999, and 2000; a second treatment was burned twice, in the late winter of 1996 and 2000. On Whittleton Ridge, one treatment was burned twice in the late winter of 1995 and 1999 and a second treatment was burned once in the late winter of 1997. This experimental design allowed us to test the effects of fire frequency (number of burns) on stand structure and understory light environment.

Prescribed fires were conducted by the USDA Forest Service personnel of the Stanton Ranger

Table 1. Median fire temperature ranges (°C) and weather conditions of each prescribed fire event. Dashes indicate years without burning.

Conditions	1995	1996	1997	1998	1999	2000
Klaber 3× burn (1995, 1999, 2000)						
Burn date	3/17	—	—	—	3/26	3/30
Temp. at 15 cm aboveground (°C)	316–398	—	—	—	400–499	500–659
Temp. at surface (°C)	316–398	—	—	—	198–249	250–399
Air temp. (°C)	21	—	—	—	8	9
Relative humidity (%)	36	—	—	—	40	35
Flame length (m)	0.3–0.9	—	—	—	0.3–0.9	0.3–0.9
Klaber 2× burn (1996, 2000)						
Burn date	—	3/13	—	—	—	3/30
Temp. at 15 cm aboveground (°C)	—	399–481	—	—	—	500–569
Temp. at surface (°C)	—	204–315	—	—	—	250–399
Air temp. (°C)	—	18	—	—	—	9
Relative humidity (%)	—	25	—	—	—	35
Flame length (m)	—	0.3–0.9	—	—	—	0.6–0.9
Whittleton 2× burn (1995, 1999)						
Burn date	3/15	—	—	—	3/26	—
Temp. at 15 cm aboveground (°C)	204–315	—	—	—	500–659	—
Temp. at surface (°C)	316–398	—	—	—	198–249	—
Air temp. (°C)	23	—	—	—	11	—
Relative humidity (%)	29	—	—	—	40	—
Flame length (m)	0.3–0.9	—	—	—	0.3–0.9	—
Whittleton 1× burn (1997)						
Burn date	—	—	3/24	—	—	—
Temp. at 15 cm aboveground (°C)	—	—	na	—	—	—
Temp. at surface (°C)	—	—	na	—	—	—
Air temp. (°C)	—	—	13	—	—	—
Relative humidity (%)	—	—	45	—	—	—
Flame length (m)	—	—	0.3–0.6	—	—	—

District. All burns were conducted in March, regardless of year, reflecting the Forest Service goal of conducting late winter prescribed fires. Burn conditions (air temperature, relative humidity, and flame length) were recorded by Forest Service personnel on the day of the burn. Temperatures were recorded using six different Tempilac® temperature-sensitive paints representing a range from 93 °C to 576 °C painted on aluminum tags (Blankenship and Arthur 1999). Table 1 summarizes the burn conditions in the four burn treatments in each burn year.

FIELD SAMPLING. Eight 0.05 ha permanent circular plots at each of the 6 treatments were established at random to measure the vegetation. We used data on the midstory (DBH 2–15 cm; collected from 1995 to 2001) and shrub (DBH < 2 cm, height > 50 cm; collected in 2000 and 2001) strata to characterize the effects of fire on stand structure.

Two 100 m transects were established at each of the six treatments in August 2000. At 20-meter intervals along each transect, the nearest seedling of each species, chestnut oak (*Q. prinus*), scarlet oak (*Q. coccinea*) and red maple (30 seedlings per site, 180 seedlings total), was marked with a flag for repeated measurements of understory gap fraction. Hemispherical photographs were taken 60 cm above each seedling in the summer of 2000 and 2001 to estimate gap fraction. Each pair of hemispherical photos was taken at the same spot in different years (see Fig. 5). Gap fraction is the percentage of total sky area that is not blocked by vegetation (Bellow and Nair 2003). By characterizing the canopy structure, hemispherical photography has been extensively used as a surrogate measure of the light environment (e.g., Canham et al. 1990, Lerdau et al. 1992, Whitmore et al. 1993, Canham et al. 1994, Bellingham et al. 1996, Pearcy and Yang 1996, Breshears et al. 1997, Nicotra et al. 1999), demonstrating a close relationship between gap fraction and direct measures of light availability (Rijkers et al. 2000, Hale 2003, Bellow and Nair 2003, Battaglia et al. 2003).

Hemispherical photographs were taken using a Nikon Cool-Pix 950 digital camera with a Nikon FC-E8 183° fisheye converter. The photo-

graphs were taken during dusk and dawn, or on cloudy days, to prevent direct sunlight from entering the image. The digital images were first edited using Adobe Photoshop to eliminate noise and reflection, and then analyzed using GLA Version 2.0 canopy image analysis software (Frazer et al. 1999). The pixels within each image were classified into either sky or non-sky classes by assigning a threshold value, ranging from 0 to 255 (Frazer et al. 1999). Determination of the threshold value can cause biases in analyzing hemispherical photographs due to the incorporation of operator subjectivity (de Freitas and Enright 1995, Roxburgh and Kelly 1995). However, the operator biases can be insignificant with proper training before analysis (Robison and McCarthy 1999). To minimize the potential operator bias all photographs were analyzed in random order by the same person and each photograph was analyzed repeatedly until two measurements of gap fraction were within 0.5% of each other (Canham et al. 1990, Oberbauer et al. 1993). Other field protocols and details of hemispherical photography conformed to those described in Rich et al. (1999).

DATA ANALYSIS. We applied repeated-measures analysis of variance (von Ende 2001) to test the impacts of prescribed burning (between subject factor) on the midstory stem density and understory gap fraction, which were measured in 2000 and 2001. The influence of the year of measurement (within subject factor) was also tested to examine whether midstory stem density and understory gap fraction underwent short-term recoveries from prescribed burning. With each treatment site defined as the experimental unit, the arithmetic mean of midstory stem density and understory gap fraction at each treatment was used for the analysis of variance. For each site, a two sample paired t-test was also performed to examine the temporal change (between 2000 and 2001). All terms in repeated-measures ANOVA models were considered fixed effects and therefore were tested using the residual (error) mean square. Repeated-measures ANOVA and regression analysis were run with the GLM procedure in SAS (SAS Institute 2000). Probability values less than 0.05 were considered to be statistically significant.

Results and Discussion. EFFECT OF FIRE ON MIDSTORY STEM DENSITY. Prescribed burning had a significant effect on midstory stem density (stems 2–15 cm DBH; $P = 0.0061$; Table 2).

Table 2. Repeated measures analysis of variance on the effect of prescribed burning on midstory stem density (stems 2–15 cm dbh). Treatment (burned vs. unburned) was considered the main effect for between subject factors. Two consecutive years of measurements were considered the main effect for within subject factors. The means of stem density at different sites and years were used for this analysis.

Source of variation	df	MS	*F*	*P*
Between subjects				
Treatment	1	1264315.51		
Error	4	45168.04	27.99	0.0061
Within subject				
Year	1	3015.04		
Year*Treatment	1	536.76	1.87	0.2429
Error (year)	4	1608.90	0.33	0.5945

Midstory stem density on each burned treatment exhibited substantial reduction after each prescribed fire (Fig. 1). The differences in midstory stem density between pre-burn (1995) and 2001 were significantly correlated with the number of burns ($R^2 = 0.86$, $P = 0.0076$; Fig. 2). The significant intercept ($P = 0.0482$) reflects the decline of midstory stem density even in the absence of prescribed burning (two reference treatment sites). This decline was caused by the 93–98% mortality of dogwood as a result of dogwood anthracnose (*Discula destructiva*) infection, and competition among all midstory stems exacerbated by drought during the late 1990s (McEwan et al. 2000, M. A. Arthur unpublished data). Despite the background decline in midstory stem density, each burn further reduced midstory stem density by approximately 550 stems per hectare (based on the simple regression model). Although this impact tended to attenuate with an increasing number of burns, the quadratic term in the polynomial regression model was not significant ($P = 0.2838$). Our findings agree with Peterson and Reich (2001), who showed a significant relationship between fire frequency and mean annual density change.

There was not a significant difference in stem density between 2001 and 2000 ($P = 0.2429$; Table 2) based on the repeated measures analysis of variance. Two sample paired t-tests revealed no significant changes in midstory stem density between 2001 and 2000 except for the Klaber 2× burn site, which had a significant decline (Fig. 3A). The decline in midstory stem density between 2001 and 2000 at Klaber 2× burn site was primarily due to the loss of red maple. Thus, fire frequency significantly reduced midstory stem density, and this impact was maintained in

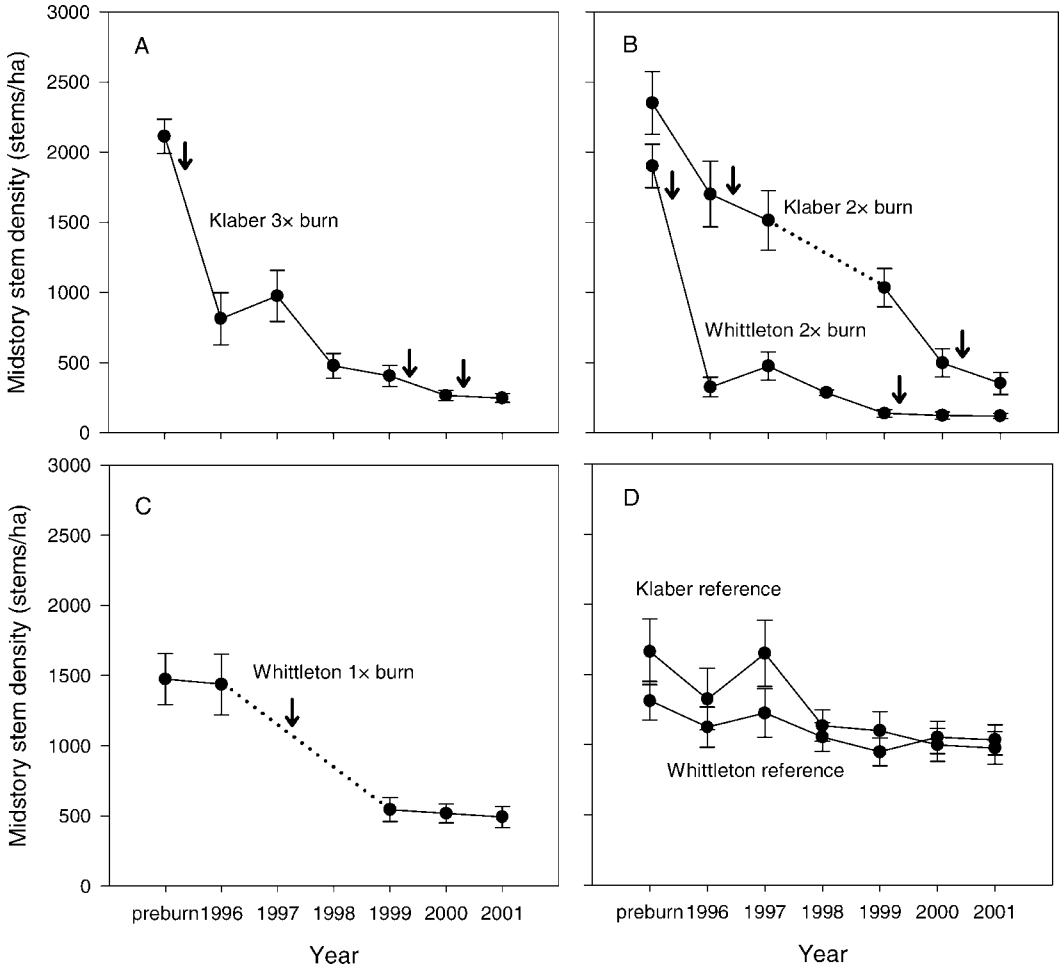


FIG. 1. Midstory stem density (stems 2–15cm DBH) in treatments with A: 3× burns, B: 2× burns, C: 1× burn, and D: unburned reference. Arrows indicate the time of burning. Dotted lines indicate missing data. Error bars represent ± 1 SE. The preburn measurements were made in January 1995; in all other years, measurements were made in August.

the midstory stratum without significant ingrowth between 2001 and 2000. Because oaks were not important in the midstory stratum in these sites prior to burning (< 6% in relative density), stem density losses due to prescribed burning were less than those of fire-sensitive species (M. A. Arthur unpublished data). In general, short fire intervals would be expected to favor dominant pines, blackgum, sourwood and chestnut oak over red maple and thin-barked, slow-growing species such as *Carya* spp. and scarlet oak (Harmon 1984).

EFFECT OF FIRE ON GAP FRACTION. Prescribed fire did not have a significant impact on gap fraction, measured in the understory stratum using hemispherical photography ($P = 0.1166$; Table 3) based on the repeated measures analysis of variance. However, the three treatments burned most recently and multiple times (Klaber 3× burn, Klaber 2× burn, and Whittleton 2× burn) did exhibit greater gap fraction than the treatment burned just once in 1997 (Whittleton 1× burn) and the two reference treatments (Fig. 4). We attribute this increase in gap fraction to the thinning effect of recurrent prescribed fire on midstory stem density (Fig. 1 and 2) because shrub layer density is low on the reference site and prior to burning on the treated sites, and our prescribed burning did not impact the overstory stem density.

There was a significant effect of year (2000 vs. 2001) on gap fraction ($P = 0.0293$; Table 3).

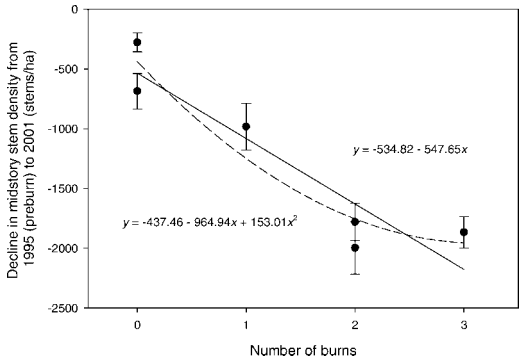


FIG. 2. The relationship between the decline in midstory stem density from 1995 (preburn) to 2001 and the number of burns. The solid line represents the simple linear regression model ($R^2 = 0.86$, $F_{1,4} = 16.03$, $P = 0.0076$). The dashed line represents the 2° polynomial regression ($R^2 = 0.91$, $F_{2,4} = 15.45$, $P = 0.0263$). Error bars are ± 1 SE.

This was corroborated by two sample paired t-tests, which demonstrated a significant decline in gap fraction at all burned sites and the Whittleton reference site (Fig. 3B). This decline in gap fraction tended to diminish with increasing number of growing seasons since the last burn (Fig. 3B); the decline was similar between the once burned treatment and the Whittleton reference treatment from 2000–2001.

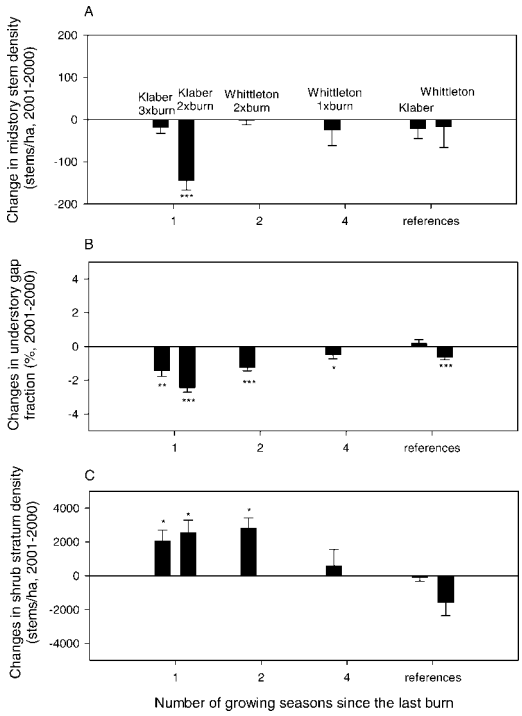


FIG. 3. The differences in the repeated measurements of midstory stem density (A), understory gap fraction (B), and shrub stratum density (C) in 2000 and 2001 (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$).

Table 3. Repeated measures analysis of variance on the effect of prescribed burning on gap fraction. Treatment (burned vs. unburned) was considered the main effect for between subject factors. Two consecutive years of measurements were considered the main effect for within subject factors. The means of gap fraction at different sites and years were used for this analysis.

Source of variation	df	MS	*F*	*P*
Between subjects				
Treatment	1	8.03	3.98	0.1166
Error	4	2.02		
Within subject				
Year	1	3.20	11.05	0.0293
Year*Treatment	1	0.87	3.00	0.1581
Error (year)	4	0.29		

As described above, the post-fire midstory stem density did not exhibit recovery from the effects of fire between 2001 and 2000 (Fig. 3A), yet there was a change in gap fraction during this period that was most pronounced in the three treatments burned multiple times. We found a rapid flush in shrub stratum density at the burned treatments (> 2000 stems/ha; Fig. 3C) that was coincident with (and opposite to) the decline in gap fraction (Fig. 3B). The increased density in the shrub stratum, which was primarily composed of stump sprouts, played an important role in the rapid reduction in gap fraction after burning. As shown in hemispherical photographs taken at the Klaber 2× burn site in

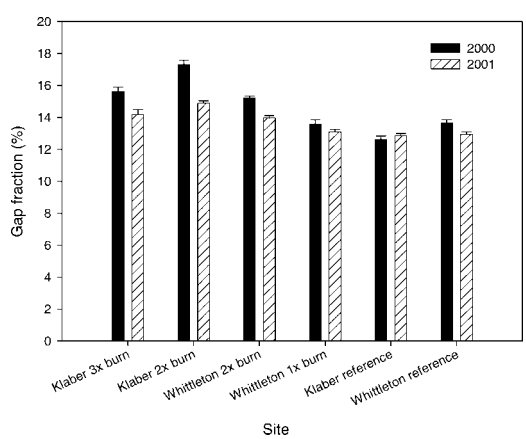
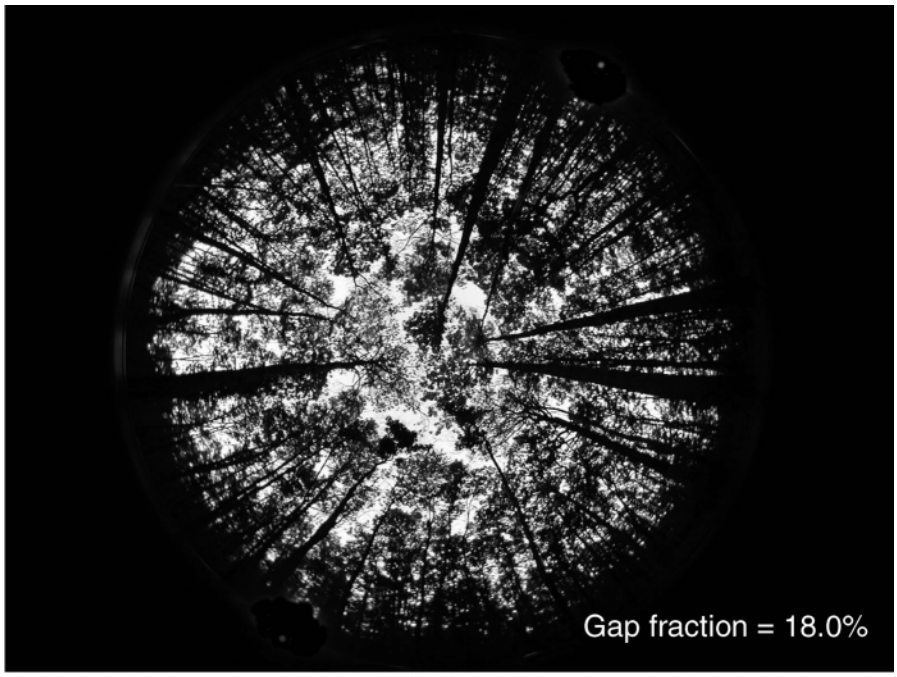


FIG. 4. The understory gap fraction measured by hemispherical photographs at each treatment in the summer of 2000 and 2001. Error bars are ± 1 SE.

A



B

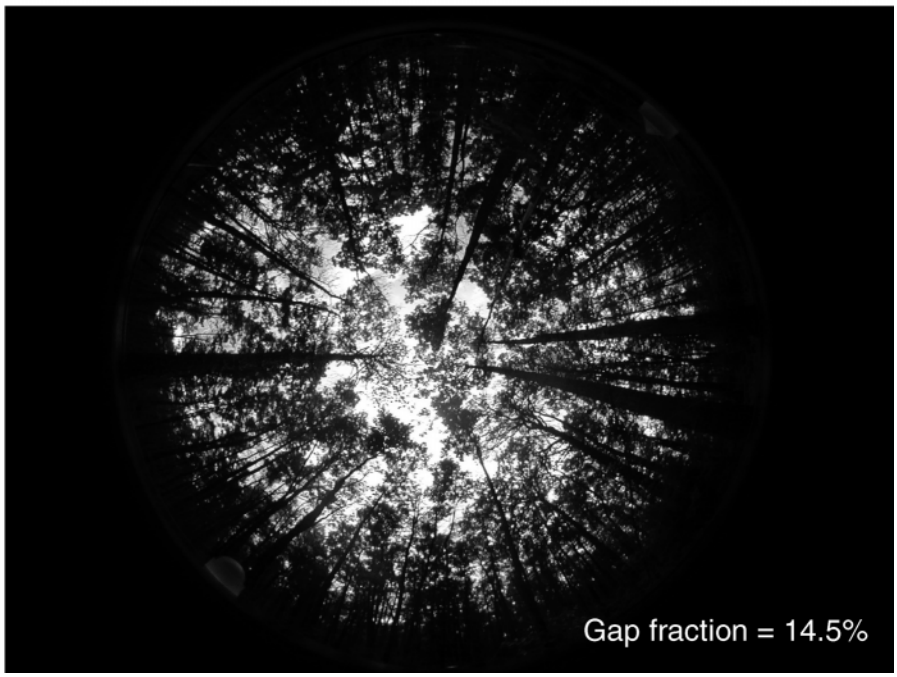


FIG. 5. Hemispherical photographs taken in the summer of 2000 (A) and 2001 (B) at Klaber 2× burn treatment. Photograph A (gap fraction = 18.0%) were taken in the same year of the last prescribed burning which was applied in late winter 2000. Photograph B (gap fraction = 14.5%), which was taken a year later, showed an increase in cover primarily at the edge of the photograph where the shrub layer most strongly influences the forest stand profile.

2000 (Fig. 5A) and 2001 (Fig. 5B), the decline in gap fraction from 18.0 to 14.5% was mainly due to the increases in vegetation near the edge of the hemispherical photograph, which represented the shrub stratum of the stand profile. The center of the two images, which represented the top of the canopy, showed very little change. This pattern of change in hemispherical photos taken in the burned sites was typical.

Prescribed burning in late winter with moderate intensity (Table 1) is typical in the attempts to restore oak regeneration in the central and Appalachian hardwood regions (Sutherland et al. 2003). Our study showed slightly greater gap fraction (3 to 5%) in the burned compared to the reference treatments following prescribed burning, probably through the reduction of midstory stem density (Fig. 1). Despite these minor changes, however, we measured significant seedling responses to fire in two studies. An earlier study of red maple and oak (chestnut and scarlet) seedlings demonstrated greater foliar concentrations of N, P, K and Mg, higher photosynthetic potential, and greater relative growth rates of diameter and height on burned sites compared to unburned sites (Gilbert et al. 2003). A companion study to this paper on seedling responses to fire demonstrated greater leaf mass per area and maximum photosynthetic rate in response to the increases in gap fraction at both Klaber burned sites (Chiang 2002), suggesting that even a minor change in gap fraction could improve seedling performance. However, due to the rapid flush of stump sprouts, increases in gap fraction were diminished with increasing number of growing seasons since the last burn.

Although the canopy trees intercept most of the light in hardwood forest stands, the midstory co-dominant and understory shrub strata also have important impacts on the understory light environment (Lorimer et al. 1994), and both strata are subject to the impacts of prescribed burning. Post-fire midstory density was not subject to short-term increases; in contrast, shrub layer stem density can reach three to four thousand stems per hectare in one year and approached 10,550 stems/ha in the Whittleton 1× burn (3 growing seasons since the last burn). The post-fire increase in gap fraction, achieved by the thinning effect of prescribed fire in the midstory, was quickly filled by the rapid flush of stump sprouts.

In summary, our data suggest that prescribed burning can significantly reduce the midstory stem density, thereby temporarily increasing light in the understory. However, the understory shrub stratum (mostly stump sprouts), which increased rapidly in stem density after fire, quickly mitigated the influence of canopy gaps created by prescribed fire. Managers whose goal is to increase light in the understory through the use of prescribed burning will need to control the flush of stump sprouts in the shrub layer. Prescribed fires of the type used in this study (late winter, moderate intensity) will be unlikely to maintain the necessary light environment for successful oak regeneration because of the failure of subsequent fires to cause significant mortality to root systems that repeatedly produce stump sprouts following fire. Consistently burning later in the season when sprouts are becoming physiologically active may hold some promise for effective mortality of stump sprouts and deserves investigation. However, accurate timing of prescribed burns to phenological status of plants is difficult for managers tasked with burning large areas.

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