RESEARCH ARTICLE

LONG-TERM EFFECTS OF HIGH INTENSITY PRESCRIBED FIRE ON VEGETATION DYNAMICS IN THE WINE SPRING CREEK WATERSHED, WESTERN NORTH CAROLINA, USA

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ABSTRACT

We examined the long-term effects of a prescribed fire in a southern Appalachian watershed in Nantahala National Forest, western North Carolina, USA. Fire was prescribed in 1995 on this site by forest managers to restore a degraded pine (*Pinus* spp.)-hardwood community, specifically to stimulate forage production, promote pine and oak (*Quercus* spp.) regeneration, and increase plant diversity. Before and after the prescribed fire, permanent plots were sampled across a south-facing hillslope, which corresponded to three community types: mesic, near-stream cove (riparian); dry, mixed-oak (mid-slope); and xeric, pine-hardwood (ridge). In an earlier paper, we reported the first two years of post-burn vegetation response from this prescribed burn. In our current study, we compared the pre-burn (1994) forest condition with 10 years post-burn (2005) vegetation measurements to determine the effects of fire on the mortality and regeneration of overstory trees, understory shrubs, and herbaceous-layer species. Overstory mortality was high immediately after the burn at the ridge location and ten years after the fire. Mortality of pitch pine (*Pinus rigida* Miller) (91.8%) and hickory (*Carya* spp.) (77.5%) reduced overstory basal area from 26.97 m^2 ha^{-1} pre-burn to 18.86 m^2 ha^{-1} post-burn in 1995 and to 9.13 m^2 ha^{-1} in 2005. At the mid-slope and riparian locations, no significant overstory mortality occurred over time. Understory density was significantly higher 10 years after the burn (2005) than pre-burn, and basal area had returned to pre-burn levels. Density of mountain laurel (*Kalmia latifolia* L.), black huckleberry (*Gaylussacia baccata* [Wang.] K. Koch), and blueberry (*Vaccinium* spp.) had increased due to prolific sprouting. The prescribed fire had varying effects on diversity across the hillslope gradient over time. On the ridge, overstory diversity declined following the fire ($H'_{\text{basal area}}$ = 1.14 in 1994, $H'_{\text{basal area}}$ = 0.75 in 1995, and $H'_{\text{basal area}}$ = 0.80 in 2005). Diversity significantly increased in the herbaceous layer and remained higher than pre-burn conditions through 2005 (H'_{cover} = 1.02 in 1994, H'_{cover} = 1.97 in 1995, and H'_{cover} = 2.25 in 2005). For the mid-slope and riparian positions, no change in diversity was observed in the overstory, understory or herbaceous layer.

Keywords: *Carya* spp., diversity, herbaceous flora, *Kalmia latifolia,* mortality, pine-oak heath, restoration, *Pinus rigida*, *Quercus* spp.

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INTRODUCTION

Prescribed burning is currently being used as a management tool to reduce fuel loads, improve wildlife habitat, and to restore ecosystem structure and function in the southern Appalachian forests of the USA that are managed by the Forest Service, the National Park Service, and The Nature Conservancy. Historically, fire was an integral part of the Appalachian forests and determined their natural structure and composition (Barden and Woods 1976, Harmon 1982, Buckner 1989, Van Lear and Waldrop 1989, DeVivo 1991, Brose *et al.* 2001, Brose and Waldrop 2006, Petersen and Drewa 2006). In particular, mixed pine-hardwood forest types occupying dry ridge sites were thought to be dependent on fire for their maintenance (Barden and Woods 1976, Barden 2000, Lafon *et al.* 2007). Fire suppression and the limited occurrence of natural fires in xeric pine-hardwood forests have promoted the dominance of hardwoods, and the pine component has been in decline for about three decades (Smith 1991, Vose *et al.* 1994, Elliott and Vose 2005). In addition, substantial drought-related insect populations (primarily southern pine beetle [*Dendroctonus frontalis* Zimmermann]) (Hoffmann and Anderson 1945, Smith 1991, Elliott *et al.* 1999*a*, Elliott and Vose 2005) and previous land use practices, such as high-grading, have contributed to further changes in these forests. The result is a significant increase in acreage of stands with a dense understory of mountain laurel (*Kalmia latifolia* L.), an evergreen ericaceous shrub, on upper, drier slopes. Competition with mountain laurel inhibits the reproduction and growth of both woody and herbaceous vegetation so that changes in species composition and stand structure are likely to persist without management intervention

The mixed-oak (*Quercus* spp.) stands that occupy mesic, sub-mesic, and dry forests at middle elevations are also undergoing considerable change. Oaks were a dominant feature of the southern Appalachians long before European settlement (Clark and Robinson 1993, Abrams 2005), and throughout the entire region various species of oak remain major components of many forest types (Nowacki and Abrams 1992, Stephenson *et al.* 1993). However, the decline in oak abundance across the eastern US has been documented in numerous studies (Oak *et al.* 2004, Abrams 2005, Guldin *et al.* 2006, Heitzman *et al.* 2007). These submesic to dry oak forests were established and historically maintained by a combination of natural and human-induced fires (Lorimer 1984, Abrams and Nowacki 1992). In the absence of fire, shade-tolerant species, such as red maple (*Acer rubrum* L.), that formerly were confined to the understory have become established and are recruiting into the overstory at unprecedented rates (Lorimer 1985, Crow 1988, Elliott *et al.* 1999*b*, Galbraith and Martin 2005, Rentch and Hicks 2005, Fei and Steiner 2007, Elliott and Swank 2008).

In the southern Appalachians, fire has been prescribed as a silvicultural treatment in pine-hardwood forests to restore diversity and productivity (Swift *et al.* 1993) and to promote regeneration of native pines and oaks (Vose *et al.* 1994, Vose *et al.* 1997). Fire can reduce the abundance of mountain laurel and delay its growth (Clinton *et al.* 1993), encourage oaks and various other tree species to sprout (Van Lear and Waldrop 1989), and provide a seedbed where native pines can germinate and become established (Elliott *et al.* 1999*a*, Waldrop and Brose 1999, Waldrop *et al.* 2000).

Much is known about short-term vegetation responses to fire in the southern and central Appalachians (Johnson 1985, Van Lear and Waldrop 1989, Van Lear and Watt 1993, Elliott *et al.* 1999*a*, Welch *et al.* 2000, Van Lear *et al.* 2004, Elliott and Vose 2005, Signell *et al.* 2005), but few studies document longer-term responses (Blankenship and Arthur 2006). Long-term studies are necessary for evaluating and predicting the response of mixed-oak/pine communities following wildland fire.

In this study, we examined the longer-term effects of a single, dormant season fire in the Nantahala National Forest, western North Carolina, USA. In 1995, the fire was ignited across a south-facing slope, an area where fire had been excluded for over 70 years. The purpose of the burn was to create a mosaic of fire intensities to restore a pine-hardwood community, stimulate forage production, reduce the understory biomass of mountain laurel and shade-tolerant hardwood species, and promote pine and oak regeneration along the hillslope gradient. In earlier papers, we compared the first two years of responses to the pre-burn forest condition (Elliott *et al.* 1999*a*, Vose *et al.* 1999). This current paper addresses the longer-term effects 10 years after a single, prescribed fire.

METHODS

Study Area

The study area is located in the Nantahala National Forest in the southern Appalachian Mountains of western North Carolina (35°N latitude, 83°W longitude) and is part of the Wine Spring Creek Ecosystem Management Project (Swank *et al.* 1994). The Wine Spring Creek watershed is within the Blue Ridge Mountains District of the Blue Ridge physiographic province. The area has a southern aspect and elevations range from 1500 m to 1700 m with slopes ranging from 35 % to 60 %. The soil types along the upper slope and ridge are fine-loamy, mixed, mesic Typic Hapludults (Edneyville Series) and loamy, mixed, mesic Lithic Dystrochrepts (Cleveland Series); and the soils along the middle and lower slope positions are coarse-loamy to a loamy-skeletal, mixed, mesic Typic Haplumbrepts (Cullasaja Series) (Thomas 1996). Mean annual temperature is 10.4 °C and mean annual precipitation is 1900 mm (Coweeta Hydrologic Laboratory, unpublished data).

A prescribed burn of approximately 300 ha was conducted in April 1995. The fire was ignited by helicopter at the bottom of the south facing slope near the stream. It created a mosaic of fire intensities across the hillslope, ranging from lightly burned (flame temperatures < 80 °C) at the low slope to heavily burned (flame temperatures > 800 °C) along upper slopes and ridges (Vose *et al.* 1999). Heat penetration into the soil also varied along the hillslope. On the ridge, a 45 °C heat pulse penetrated 27.5 mm and a 59 °C heat pulse penetrated 24.0 mm. On the mid-slope, a heat pulse penetrated 18.2 mm and 16.8 mm for 45 °C and 59 °C, respectively. On the lower slope, a heat pulse penetrated less than 0.6 mm and temperatures never exceeded 45 °C (Vose *et al.* 1999). In the areas of highest fire intensity, along the ridge, a stand-replacing fire consumed understory vegetation and ignited the crowns (Vose *et al.* 1999).

Experimental Design

Before the prescribed burn, 32 plots were established along seven parallel transects that ran from the top of the ridge to the stream (Elliott *et al.* 1999*a*). In July 1994, twelve 15 m × 15 m plots were sampled and an additional twenty 10 m × 10 m plots were sampled in March 1995 before the burn. After the burn, plots were sampled again in July of 1995, July 1996 (Elliott *et al.* 1999*a*), and July 2005 (10 years post-burn). Plot locations along transects corresponded to three community types: mesic, near-stream cove (riparian); dry, mixed-oak (mid-slope); and xeric, pine-hardwood (ridge). In 2005, only 25 of the original 32 plots could be located and re-measured (n = 13 ridge plots; n = 6 slope plots; and n = 6 riparian plots). These 25 plots were used for the statistical analyses to compare pre-burn (1994) and early responses (1995 and 1996) to 10 years post-burn (2005) vegetation responses to prescribed fire.

As with many other large scale fire studies, this study was pseudoreplicated (van Mantgem *et al.* 2001). Therefore, interpretation is based on before, after, and long-term burn treatment effects and limited to this particular forest site. However, case studies of large scale events still provide valuable information as long as they are interpreted appropriately (Turner *et al.* 1997, van Mantgem *et al.* 2001).

Overstory and Understory Sampling

Vegetation was measured by layer: the overstory layer included all trees ≥5.0 cm diameter at breast height (dbh, 1.37 m above ground); the understory layer included all woody stems <5.0 cm dbh and ≥1.0 cm basal diameter; and the herb-layer included woody stems <1.0 cm basal diameter and all herbaceous species. Woody stems with <1.0 cm basal diameter were counted as seedlings regardless of the mode of reproduction (i.e., seedling or sprout origin).

Diameter of all overstory trees was measured and recorded by species in every plot. For the original plots, the understory layer was measured and recorded by species in the entire 15 m × 15 m plot, with the exception of mountain laurel and flame azalea (*Rhododendron calendulaceum* [Michaux] Torrey). These were measured in a 3.75 m × 3.75 m subplot in the southwest corner of each plot. For the additional plots, the understory layer (including mountain laurel, great laurel [*Rhododendron maximum* L.] and flame azalea) was measured in a 3.0 m × 3.0 m subplot located in the southwest corner of each plot (Elliott *et al.* 1999*a*).

Herbaceous Layer Sampling

Only six ridge plots were sampled for herbaceous layer species before the burn in 1994 and re-sampled post-burn in 1995 and 1996 (Elliott *et al.* 1999*a*), and again in 2005. Cover of herbaceous layer species was estimated visually by cover classes in six 1.0 m^2 quadrats placed in the corners and at the midpoint of the east and west sides of each plot (a total of 36 quadrats). The seven cover classes used were: R (0% to 0.5%), 1 (0.5% to 1%), 2 (>1% to 3%), 3 (>3% to 15%), 4 (>15% to 33%), 5 (>33% to 66%), and 6 (>66%). In the analyses, midpoint values of each cover class were used to compare pre-burn and post-burn effects.

Tree seedling abundance was estimated for the 25 plots sampled before and after the burns is 1995, 1996, and again in 2005 after the prescribed burn. Tree seedlings were counted in each 1.0 m^2 quadrat of the original plots and in the 3.0 m × 3.0 m subplots of the additional plots. Tree species nomenclature follows Kirkman *et al.* (2007) and nomenclature for all other flora follows Gleason and Cronquist (1991).

Data Analyses

We used several indices—species richness (S), Shannon-Weiner's index of diversity (H'), and Pielou's (1966) evenness index (J')—to evaluate the change in vegetation diversity from pre-burn 1994 to post-burn 2005. Shannon-Weiner's index is a simple quantitative expression that incorporates both species richness and the evenness of species abundance (Magurran 2004), and was calculated based on stem density (stems ha^{-1}) or basal area (m^2 ha^{-1}) of woody species, and percent cover of herbaceous species. Separate statistical analyses were performed for each vegetative layer (i.e., overstory, understory, and herbaceous layer). Because the permanent plots were sampled over time, we used a mixed linear model with repeated measures (PROC MIXED, SAS 2002-2003, Cary, North Carolina, USA) to determine significant vegetation differences between years. We used the unstructured covariance option in the repeated statement because it produced the lowest AIC value. If the overall F-tests were significant ($P < 0.05$), then least squares means (LS-means, Tukey-Kramer adjusted t-statistic) tests were used to determine significant differences between years (Littell *et al.* 1996).

RESULTS

Overstory

On the ridge, 10 year post-fire mortality of pitch pine (*Pinus rigida*) (92.7%) and hickory (*Carya* spp.) (77.5%) significantly reduced overstory density and basal area (Table 1). Before the prescribed fire (1994), pitch pine, chestnut oak (*Quercus montana* Willdenow), hickory, and scarlet oak (*Quercus coccinea* Munch.) were the most abundant overstory species, accounting for 72% of the density and 78% of the basal area (Table 2). Ten years after the fire, chestnut oak, red maple, serviceberry (*Amelanchier arborea* [Michaux f.] Fernald), and sourwood (*Oxydendrum arboreum* [L.] De Candolle) were the most abundant, accounting for 70% of the density and 49% of the basal area. In addition, H'$_{\text{basal area}}$ declined the first year after burning but no difference was detected between pre-burn and 2005.

Table 1. Average overstory[a] density, basal area, and diversity based on density (H'$_{\text{density}}$) and basal area (H'$_{\text{basal area}}$) before the prescribed burn (1994), and the first (1995) and tenth (2005) growing seasons after the prescribed burn for the three communities (ridge, mid-slope, and riparian) at Wine Spring Creek, western North Carolina.

	Pre-burn 1994	1 yr post-burn 1995	10 yr post-burn 2005
Ridge (n = 13)			
Density (stems ha^{-1})[a]	1582 (142) A[b]	979 (189) B	637 (96) B
Basal area (m^2 ha^{-1})	26.97 (2.14) A	18.86 (3.24) A	9.13 (2.33) B
H'$_{\text{density}}$	1.28 (0.13) A	0.84 (0.17) A	0.87 (0.11) A
H'$_{\text{basal area}}$	1.14 (0.09) A	0.75 (0.14) B	0.80 (0.09) AB
Mid-slope (n = 6)			
Density (stems ha^{-1})	1550 (305) A	1500 (303) A	917 (262) A
Basal area (m^2 ha^{-1})	31.02 (6.82) A	30.80 (6.78) A	24.06 (8.38) A
H'$_{\text{density}}$	1.19 (0.15) A	1.17 (0.14) A	1.04 (0.23) A
H'$_{\text{basal area}}$	0.99 (0.14) A	0.99 (0.14) A	0.96 (0.21) A
Riparian (n = 6)			
Density (stems ha^{-1})	1150 (158) A	1150 (159) A	1050 (159) A
Basal area (m^2 ha^{-1})	28.95 (6.51) A	28.95 (6.51) A	29.00 (5.79) A
H'$_{\text{density}}$	1.33 (0.16) A	1.33 (0.16) A	1.21 (0.16) A
H'$_{\text{basal area}}$	1.08 (0.07) A	1.08 (0.07) A	0.96 (0.13) A

[a] Overstory woody stems are ≥ 5.0 cm dbh.
[b]Values in rows followed by different letters are significantly different ($p < 0.05$) based on repeated measures analysis of variance, followed by Tukey-Kramer adjusted t-test. Standard errors are in parentheses.

Table 2. Overstory species[a] density (stems ha^{-1}) and basal area (m^2 ha^{-1}) before the prescribed burn (1994), and the first (1995) and tenth (2005) growing seasons after the burn for the three communities (ridge, mid-slope, and riparian) at Wine Spring Creek, western North Carolina.

	Pre-burn		1 yr post-burn		10 yr post-burn	
	Density	**Basal area**	**Density**	**Basal area**	**Density**	**Basal area**
Ridge (n = 13)						
Acer rubrum	116	2.31	51	1.32	83	1.67
Amelanchier arborea	114	1.03	90	0.77	76	1.08
Carya spp.	138	1.48	54	0.86	31	0.77
Oxydendrum arboreum	100	1.67	83	1.46	68	1.42
Pinus rigida	618	12.36	420	9.58	51	0.38
Quercus coccinea	131	2.43	68	1.68	57	0.47
Quercus montana	250	4.80	182	2.92	218	3.03
Mid-slope (n = 6)						
Acer rubrum	650	8.29	650	8.29	300	6.50
Carya spp.	133	2.07	133	2.07	117	2.49
Nyssa sylvatica	233	1.49	233	1.49	200	1.89
Oxydendrum arboreum	133	2.79	117	2.76	83	2.42
Quercus coccinea	50	5.92	33	5.78	17	2.06
Quercus montana	133	7.94	133	7.94	83	7.56
Riparian (n = 6)						
Acer rubrum	367	7.36	367	7.36	300	8.55
Carya spp.	183	7.90	183	7.90	150	4.48
Oxydendrum arboreum	33	1.18	33	1.18	33	1.47
Quercus alba	17	3.02	17	3.02	17	3.54
Quercus rubra	17	2.78	17	2.72	17	3.34
Tsuga canadensis	283	3.83	283	3.83	300	5.46

[a] Overstory included woody stem ≥ 5.0 cm dbh. Species nomenclature follows Kirkman *et al.* (2007*a*). Minor species (<100 stems ha^{-1} density and <1.0 m^2 ha^{-1} basal area in all years) were *Acer pensylvanicum, Acer saccharum, Amelanchier arborea, Betula lenta, Castanea dentata, Halesia carolina, Hamamelis virginiana, Liriodendron tulipifera, Magnolia acuminata, Robinia pseudoacacia,* and *Tsuga canadensis.* Species nomenclature and authorities follow Kirkman *et al.* 2007.

On the mid-slope and riparian positions, overstory density and basal area were not significantly different ten years after the burn compared to pre-burn conditions (Table 1). Red maple, blackgum (*Nyssa sylvatica* Marshall), and hickory remained the most abundant species (Table 2), with fewer scarlet oak and chestnut oak (Table 2). No differences in $H'_{density}$, or $H'_{basal\ area}$ were detected for the mid-slope or riparian communities between pre-burn and 10 years post-burn (Table 1).

Understory

The fire affected the understory vegetation layer on the ridge much more than on the mid-slope and riparian positions. Even though density and basal area were reduced the first year after burning on the ridge, by 2005 density was significantly higher and basal area had returned to the pre-burn level (Table 3). Before the burn, understory density and basal area were high on the ridge and mid-slope with mountain laurel contributing 73 % and 66 % of the density on the ridge and mid-slope, respectively

Table 3. Average understory[a] density, basal area, and diversity based on density ($H'_{density}$) and basal area ($H'_{basal\ area}$) and species richness (S) before the prescribed burn (1994), and the first (1995), second (1996), and tenth (2005) growing seasons after the prescribed burn for the three communities (ridge, mid-slope, and riparian) at Wine Spring Creek, western North Carolina.

	Pre-burn	1 yr post-burn	2 yr post-burn	10 yr post-burn
Ridge (*n* = 13)				
Density (stems ha^{-1})				
Total	13 391 (3 208) A[c]	482 (199) B	7 798 (2 149) AB	30 919 (4 443) C
K. latifolia	9 774 (2 978) A	267 (176) B	181 (170) B	19 808 (4 834) C
Tree species	3 446 (705) AB	215 (100) A	7 275 (2 216) B	7 692 (1 292) B
Shrub species[b]	9 945 (2 958) A	266 (176) A	523 (368) A	23 227 (4 449) B
Basal area (m^2 ha^{-1})	7.53 (2.21) A	0.40 (0.21) B	1.56 (0.48) B	10.58 (1.20) A
Diversity				
Plot $H'_{density}$	1.03 (0.15) A	0.49 (0.24) B	0.72 (0.17) A	0.89 (0.14) A
Plot $H'_{basal\ area}$	0.78 (0.12) A	0.64 (0.27) A	0.66 (0.15) A	0.95 (0.14) A
S / plot[d]	5.0 (0.6) A	3.6 (0.4) B	4.8 (0.5) A	4.7 (0.4) A
Mid-slope (*n* = 6)				
Density (stems ha^{-1})				
Total	10 638 (3 784) A	1 783 (1 042) B	2 675 (930) B	14 476 (6 219) A
K. latifolia	7 037 (2 878) A	185 (185) B	370 (234) B	7 911 (3 558) A
Tree species	1 851 (892) A	741 (549) A	1 481 (794) A	5 185 (2 907) A
Shrub species[b]	8 787 (3 029) A	1 042 (1 042) A	1 194 (782) A	9 291 (4 026) A
Basal area (m^2 ha^{-1})	10.85 (4.26) A	2.52 (0.74) A	2.88 (2.00) A	5.00 (1.88) A
Diversity				
Plot $H'_{density}$	0.78 (0.11) A	0.16 (0.10) A	0.33 (0.14) A	0.70 (0.19) A
Plot $H'_{basal\ area}$	0.56 (0.05) A	0.19 (0.15) A	0.32 (0.14) A	0.72 (0.19) A
S / plot[d]	4.0 (0.7) A	3.8 (0.3) A	3.7 (0.3) A	4.2 (0.3) A
Riparian (*n* = 6)				
Density (stems ha^{-1})				
Total	1 481 (1 481) A	2 407 (926) A	3 148 (1 446) A	2 490 (446) A
Tree species	0	1 333 (648) A	1 778 (566) A	1 778 (444) A
Shrub species[b]	1 481 (1 481) A	1 296 (727) A	1 667 (1 667) A	1 009 (499) A
Basal area (m^2 ha^{-1})	0.56 (0.70) A	0.66 (0.40) A	1.46 (0.75) A	0.62 (0.32) A
Diversity				
Plot $H'_{density}$	0.38 (0.08) A	0.66 (0.25) A	0.60 (0.18) A	0.57 (0.20) A
Plot $H'_{basal\ area}$	0.40 (0.08) A	0.64 (0.23) A	0.46 (0.19) A	0.34 (0.14) A
S / plot[d]	1.2 (0.2) A	2.3 (0.4) A	2.7 (0.3) A	2.5 (0.4) A

[a] Understory woody stems are < 5.0 cm dbh, ≥ 1.0 cm basal diameter.
[b] Shrub species included: *Crataegus* sp., *Gaylussacia baccata, Kalmia latifolia, Lyonia ligustrina, Pyrularia pubera, Rubus* sp., *Smilax* spp, *Rhododendron calendulaceum, Rhododendron maximum, Rhus copallina, Vaccinium corymbosum, V. vacillans, and V. stamineum.* Species nomenclature and authorities follow Gleason and Cronquist 1991.
[c] Values in rows followed by different letters are significantly different ($p < 0.05$) based on repeated measures analysis of variance, followed by a Tukey-Kramer adjusted *t*-test.
[d] Species richness was calculated as average number of species per plot. Standard errors are in parentheses.

(Table 3). On the ridge, by 2005, mountain laurel and other shrubs exceeded their pre-burn density level and total density of woody stems was significantly higher than before the burn (Table 3). On the mid-slope, mountain laurel and other shrubs returned to their pre-burn density. Density of tree species also returned to their pre-burn level by 2005 (Table 3). On average, understory tree density was twice as high in 2005 as it had been before the burn; however, this increase was not highly significant (ridge; 1994 vs. 2005, t = -2.37, P = 0.0955). On the ridge, chestnut oak and scarlet oak density remained high through 2005, while red oak and black oak (*Quercus velutina* Lamarck) had not returned to the understory (Table 4). Red oak did recruit into the mid-slope community, however, with 741 seedlings ha^{-1} in 2005 (Table 4).

For the riparian community, density and basal area were not significantly different between pre-burn and post-burn (Table 3). We did not detect a significant change in any of the measures of diversity (i.e., S, $H'_{density}$ or $H'_{basal\ area}$) over time (Table 3).

Tree Seedling Regeneration

On the ridge, total tree seedling (woody stems <1.0 cm basal diameter) density was not different between years (Figure 1). Nonetheless, the number of seedlings increased for some species, while others decreased. Red maple consistently recruited over time with nearly 4000 and more than 8000 seedlings ha^{-1} on the ridge and mid-slope, respectively (Figure 1). Scarlet oak, chestnut oak, and red oak seedlings recruited on the ridge the first and second growing seasons after the burn, but their recruitment diminished by 2005 (Figure 1). Pitch pine seedling numbers also increased on the ridge the first growing season after the burn; however, its numbers returned to the pre-burn level by 1996, and no new seedling recruitment was recorded in 2005 (Figure 1).

On the mid-slope and riparian, total number of tree seedlings significantly increased between 1994 and 2005. Red maple and serviceberry contributed the largest number of seedlings to total recruitment in 2005, with more than 8000 seedlings ha^{-1} combined (Figure 1).

Herbaceous Layer

On the ridge, percent cover decreased the first summer after the burn, returned to pre-burn levels in the second year, and remained high through 2005 (Table 5). The H'_{cover} increased the first growing season after the burn and remained high through 2005, whereas S per plot (number of species per 1.0 m^2) increased the first growing season then returned to the pre-burn level. Number of species per site increased after the fire, and many more herbaceous species (S_H) were present 10 years after the fire than before the burn (Table 5).

The percent cover of growth forms also changed after the burn. Percent cover of deciduous shrubs, such as blueberry, black huckleberry, flame azalea, and sweet pepperwood (*Clethra acuminata* Michaux) increased after the burn and remained higher than the pre-burn condition through 2005. Percent cover of graminoids increased by 1996, and then they were no longer significantly different than the pre-burn level by 2005 (Table 5). Evergreen shrubs, primarily mountain laurel, were initially reduced after burning, while deciduous shrubs and trees increased in percent cover (Table 5). Non-woody species (herbs, grasses, and vines) also increased. Before burning, non-woody species accounted for only 2.5% of the cover; by 2005, non-woody species accounted for 11.8% of the cover.

DISCUSSION

Numerous researchers have advocated using prescribed fires to restore native pine or mixed pine-hardwood forests in the eastern US

Table 4. Understory[a] species density (stems ha^{-1}) and basal area (m^{2} ha^{-1}) before the prescribed burn (1994), and the first (1995), second (1996), and tenth (2005) growing seasons after the burn for the three communities (ridge, mid-slope, and riparian) at Wine Spring Creek, western North Carolina.

	Pre-burn		1 yr post-burn		2 yr post-burn		10 yr post-burn	
	Density	Basal area	Density	Basal area	Density	Basal area	Density	Basal area
Ridge (n = 13)								
Acer rubrum	181	0.05	14	0.01	195	0.02	513	0.23
Amelanchier arborea	82	0.03	7	0.01	55	0.004	171	0.04
Betula lenta	-	-	-	-	85	0.01	-	-
Carya spp.	89	0.02	-	-	225	0.03	256	0.04
Castanea dentata	1 025	0.58	-		701	0.24	855	0.47
Kalmia latifolia	9 808	5.98	267	0.14	181	0.43	19 808	4.65
Oxydendrum arboreum	10	0.001	10	0.001	29	0.004	397	0.20
Pinus rigida	178	0.23	-	-	342	0.04	85	0.14
Quercus alba	427	0.10	-	-	-	-	171	0.03
Quercus coccinea	318	0.08	14	0.01	2 335	0.27	2 649	2.61
Quercus montana	543	0.26	27	0.03	878	0.11	1 452	0.88
Quercus rubra	396	0.20	24	0.002	-	-	-	-
Quercus velutina	20	0.01	-	-	-	-	-	-
Rhododendron calendulaceum	219	0.10	-	-	21	0.002	171	0.17
Rhododendron maximum	-	-	-	-	-	-	940	0.14
Robinia pseudoacacia	10	0.002	-	-	1182	0.18	513	0.47
Sassafras albidum	260	0.04	123	0.20	872	0.14	598	0.17
Vaccinium spp.	-	-	-	-	342	0.03	2 307	0.34
Mid-slope (n = 6)								
Acer rubrum	370	0.65	-	-	370	0.03	3 148	0.95
Amelanchier arborea	-	-	-	-	-	-	185	0.20
Castanea dentata	741	0.18	-	-	-	-	-	-
Halesia carolina	185	0.03	556	0.08	741	0.10	926	0.61
Kalmia latifolia	7 037	6.75	185	0.63	370	1.25	7 911	2.35
Magnolia acuminata	-	-	-	-	185	0.02	-	-
Nyssa sylvatica	185	0.02	-	-	-	-	-	-
Oxydendrum arboreum	185	0.01	-	-	-	-	-	-
Pyrularia pubera	185	0.07	-	-	-	-	556	0.10
Quercus alba	185	0.01	-	-	-	-	-	-
Quercus montana	-	-	-	-	185	0.01	-	-
Quercus rubra	-	-	-	-	-	-	741	0.09
Rhododendron maximum	1 565	3.13	857	1.79	824	1.46	824	0.56
Robinia pseudoacacia			185	0.01	-	-	185	0.14
Riparian (n = 6)								
Acer pensylvanicum			185	0.02	185	0.02	370	0.03
Acer saccharium			185	0.02	185	0.03	-	-
Castanea dentata			370	0.05	370	0.04	556	0.05
Crataegus sp.			185	0.02	-	-	-	-
Fraxinus americana					185	0.03	-	-
Ilex montana			-	-	-	-	185	0.01
Magnolia acuminata			370	0.05	185	0.05	185	0.04
Pyrularia pubera	185	0.08	556	0.22	370	0.11	556	0.08
Quercus rubra					185	0.05	370	0.06
Rhododendron calendulaceum	1 296	0.48	556	0.30	1 296	0.56	185	0.03
Rhododendron maximum	-	-	-	-	-	-	83	0.32

[a] Understory woody stems are < 5.0 cm dbh, ≥ 1.0 cm basal diameter. Species nomenclature and authorities follow Kirkman *et al.* 2007.

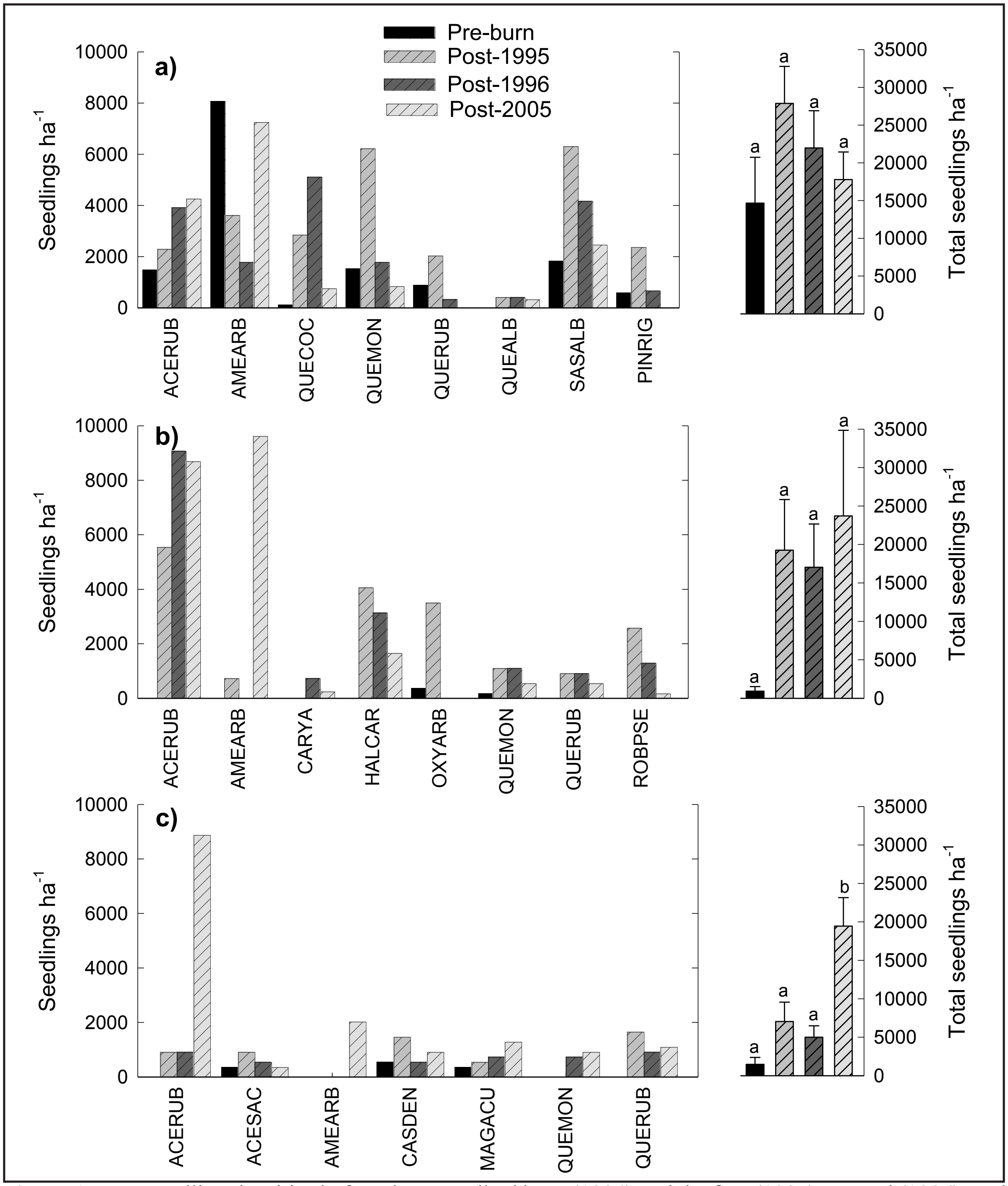

Figure 1. Tree seedling densities before the prescribed burn (1994) and the first (1995), second (1996), and tenth (2005) growing seasons after the burn: a) ridge, pine/hardwood community, b) mid-slope, mixed-oak community, and c) riparian, cove-hardwood community. Species codes: ACERUB = *Acer rubrum;* AMEARB = *Amelanchier arborea;* Carya = *Carya* spp.; HALCAR = *Halesia carolina;* OXYARB = *Oxydendron arboreum;* PRUSER = *Prunus serotina;* QUECOC= *Quercus coccinea;* QUEMON = *Quercus montana;* QUERUB = *Quercus rubra;* QUEVEL = *Quercus velutina;* ROBPSE = *Robinia pseudoacacia;* SASALB = *Sassafras albidum;* PINRIG = *Pinus rigida.* Species nomenclature and authorities follow Kirkman *et al.* (2007). Total number of seedlings have standard error bars with different letters to denote significant differences ($P < 0.05$) based on repeated measures analysis of variance (PROC MIXED 2002-2003), followed by a Tukey-Kramer adjusted *t*-test.

Table 5. Herb-layer cover, diversity (H'_{cover}), and species richness (S) and average cover by growth form before the prescribed burn (1994), and the first (1995), second (1996), and tenth (2005) growing seasons after the prescribed burn for the ridge community at Wine Spring Creek, western North Carolina.

		Cover (%)	H'_{cover}	S per plot	S per site[a]	S_W[b]	S_H[c]
1994	Pre-burn	35.57 (6.61) A[d]	1.02 (0.22) A	18.2 (0.5) AB	28	21	7
1995	1 yr post	10.58 (2.56) B	1.97 (0.33) B	22.8 (1.7) A	53	24	29
1996	2 yr post	37.67 (2.57) A	2.01 (0.08) B	12.5 (1.0) C	46	22	24
2005	10 yr post	41.06 (6.19) A	2.25 (0.08) B	14.8 (0.4) BC	60	24	36

	Cover (%)					
Growth form	**All woody**	**Trees + Deciduous shrubs**	**Deciduous shrubs**	**Evergreen shrubs**	**Forbs**	**Graminoids**
1994	33.27 A (6.89)	5.27 A (1.46)	4.22 A (1.46)	28.00 A (7.54)	1.22 A (0.35)	1.30 A (0.71)
1995	9.55 B (2.66)	5.88 A (2.87)	4.97 A (2.74)	3.67 B (1.69)	0.68 A (0.15)	0.35 A (0.18)
1996	29.38 A (1.37)	17.92 B (1.80)	12.04 AB (1.90)	11.46 B (2.15)	5.65 B (0.68)	5.38 B (1.96)
2005	28.98 A (4.84)	21.24 B (4.53)	15.91 B (3.96)	8.00 B (2.08)	9.10 C (2.05)	2.72 AB (1.90)

[a] S = total number of species for the site.
[b] S_W = number of woody species.
[c] S_H = number of herbaceous species. Ridge burn plots where herbs were measured in every year (n = 6 plots [average cover of five 1.0 m^2 quadrats per plot]). Values in columns followed by different letters are significantly different ($p < 0.05$) based on repeated measures analysis of variance (PROC MIXED 2002-2003), followed by a Tukey-Kramer adjusted t-test. Standard errors are in parentheses.
[d] Values in rows followed by different letters are significantly different ($p < 0.05$) based on repeated measures analysis of variance, followed by a Tukey-Kramer adjusted t-test.

(Dey and Hartman 2005, Elliott and Vose 2005, Van Lear *et al.* 2005, Albrecht and McCarthy 2006, Boerner *et al*. 2006, McCarthy and Brown 2006, Mitchell *et al.* 2006, Andre *et al*. 2007, Lafon *et al.* 2007).

Altered pine-hardwood communities are common across the southern Appalachian region (Van Lear and Johnson 1983, Nicholas and White 1984, Smith 1991, Swift *et al.* 1993, Clinton *et al.* 1993), and the area of altered stands has increased since the last southern pine beetle epidemic (1998 to 2002) (Elliott and Vose 2005), which induced substantial pine mortality. Altered stands are characterized by heavy mortality of native yellow pines (pitch pine, Table Mountain pine [*Pinus pungens* Lambert], and shortleaf pine [*Pinus echinata* Miller]), often with additional oak mortality, and a dense understory layer of ericaceous shrubs (e.g., mountain laurel).

The rationale for this prescribed fire was to restore the pine-hardwood forest, and we hypothesized that fire would reduce mountain laurel and fire-intolerant hardwoods (e.g., red maple, blackgum, and sourwood), stimulate wildlife forage production (i.e., grasses, herbs, forbs, and berries), increase herbaceous layer diversity, and stimulate pine and oak regeneration along the hillslope gradient. Our earlier paper reported that overstory mortality was the heaviest on the ridge and was related to fire intensity (Elliott *et al.* 1999*a*), with 31% tree mortality the first summer and no additional overstory mortality the second year after the fire. This observation was consistent with wildfire effects in a pine-hardwood forest in

West Virginia where overstory mortality was 20% after the first year and 40% after the second year (Groeschl *et al.* 1992). Even though we did not observe additional mortality the second year, by 10 years after fire on our study area, additional mortality occurred. Density was 54% lower and basal area was 66% lower than the pre-burn condition, and even lower than the first two years after the burn. This level of fire severity and concurrent tree mortality had a substantial impact on species composition and diversity.

On the ridge, overstory H' decreased after the burn due to the decline in species richness (S) rather than a change in evenness (J') of species distribution. Five species, Carolina silverbell (*Halesia carolina* L.), blackgum, white oak, red oak, and eastern hemlock (*Tsuga canadensis* [L.] Carriere), were no longer present in the overstory ten years after the burn. All were minor components of the ridge community before the burn. However, only white oak had seedlings and understory recruitment in 2005, suggesting that four of the five species may not regain their position in the overstory. For the riparian location, where fire severity was light (Vose *et al.* 1999), no changes in overstory density, basal area, or diversity were recorded.

Other studies have reported understory dominance by shade-tolerant red maple, which in the absence of fire eventually may replace oaks (Christensen 1977, Abrams 2005). In the southern Appalachians, an increase in abundance of red maple over the last two decades has been reported (Elliott *et al.* 1999*b*), and the species has become dominant, occurring across a wide range of elevation and environmental conditions (Elliott and Swank 2008). In our study, red maple, a dominant species on the ridge before the burn, suffered heavier mortality than any other hardwood overstory species (Elliott *et al.* 1999*a*), and it was also substantially reduced in the understory layer. However, by 2005, it had again recruited into the understory and overstory, and it continues to provide new seedlings across the hillslope. Conversely, chestnut oak and scarlet oak had less overstory mortality. Chestnut oak increased in importance and both oak species increased in density in the understory and herbaceous layer after the burn.

On the ridge, the increase in understory density and basal area of scarlet oak, chestnut oak, sourwood, black locust (*Robinia pseudoacacia* L.), and sassafras (*Sassafras albidum* [Nuttall] Nees) saplings after the burn corresponded to the substantial initial decrease in mountain laurel (Elliott *et al.* 1999*a*). It is possible that the fire reduced the abundance of mountain laurel and red maple long enough for oaks to overtop the evergreen shrub and successfully recruit and grow into the overstory.

The mortality and regeneration of oak saplings varied with species and intensity of the burn across the hillslope. For example, white oak, black oak, and red oak saplings suffered heavy mortality, and they have not regained their numbers in the understory layer on the ridge where the fire was most intense. In contrast, scarlet oak and chestnut oak suffered heavy mortality in the overstory (Elliott *et al.* 1999*a*). However, scarlet oak and chestnut oak seedling recruitment on the ridge was high in the first two years and, by the second year after the burn, understory density of these oaks was higher than before burning. Ten years after the prescribed fire, oak seedling numbers were low, but their numbers had more than doubled in the understory, suggesting that seedlings had successfully grown into this stratum.

The reduction of mountain laurel in the understory was sufficient to allow regeneration of oaks on the ridge and mid-slope, but the establishment of pitch pine was less successful. On our site, many mountain laurel clones survived the fire and these clones sprouted and doubled their numbers in the understory stratum ten years after the burn. Mountain laurel is a vigorous sprouter that produces many stems (McGinty 1972), but the growth of these stems is slower than that of many woody seedlings (Hooper 1969, McGee *et al.* 1995). Clinton *et al.* (1993) found that even after high intensity burning, mountain laurel reasserts its influence on microsite conditions at the forest floor within a few years and reduces the number of tree stems reaching the understory. However, the early reduction in mountain laurel abundance can allow successful establishment of native pines if pine seeds germinate, seedlings survive, and seedling growth is fast enough to overtop mountain laurel (Clinton *et al.* 1993). In our study, successful pine establishment was not the case due to low seedling survival (Elliott *et al.* 1999*a*).

Our results indicate that regeneration and re-establishment of pitch pine may not occur at Wine Spring Creek without further management. In an earlier study on this burn site, Elliott *et al.* (1999*a*) found high numbers of pine germinants the first growing season after the fire, followed by a significant decrease in pine seedlings in the second year. Ten years after the burn, we found no new pine seedlings, and pine saplings in the understory were fewer than before the prescribed fire. Elliott *et al.* (1999*a*) attributed the poor pine seedling success to three factors: 1) residual overstory basal area was too high the first year after the burn for shade-intolerant pines to survive; 2) burning consumed little of the humus layer (Vose *et al.* 1999) and roots of pine germinants probably did not penetrate to mineral soil; and 3) precipitation in early fall was well below the long-term average. Thus, most of the new germinants of pitch pine were not able to survive through the first year and succeed into the understory.

On the ridge where fire was most intense (Vose *et al.* 1999), total herbaceous layer cover decreased the first summer after the burn, and then returned to pre-burn levels by 2005. Because mountain laurel cover was substantially reduced immediately after the fire, H' increased with the recruitment of numerous herbaceous species. Ten years after the burn, deciduous shrubs and forbs continued to have higher cover than evergreen species (e.g., mountain laurel) in the herbaceous layer even though mountain laurel density had increased in the understory. Deciduous shrubs such as blueberry and black huckleberry, and grasses such as switchgrass (*Panicum* spp.) and little bluestem (*Schizachyrium scoparius* [Michaux] Nash), which increased in number after the fire, were still present even ten years later.

Several authors have found that the herbaceous layer tends to be more diverse after moderate- to high-intensity fire (Arthur *et al.* 1998, Clinton and Vose 2000, Hutchinson and Sutherland 2000, Clendenin and Ross 2001, Waldrop *et al.* 2008) partly due to removal of the litter layer, increased nutrient cycling rates, and increased light levels. In contrast, dormant season, low-intensity fire may have little to no effect on the herbaceous layer (McGee *et al.* 1995, Kuddes-Fischer and Arthur 2002, Franklin *et al.* 2003, Dolan and Parker 2004, Elliott and Vose 2005, Hutchinson *et al.* 2005).

Conclusions

Many studies in the eastern US have attributed community composition after a fire to the sprouting ability of dominant species, the failure of subordinate species to increase in numbers, and the failure of invasive species to persist (Abrahamson 1984, Schmalzer and Hinkle 1992, Matlack *et al.* 1993, McGee *et al.* 1995, Signell *et al.* 2005). In our study, all woody species sprouted, but increases in sprout densities varied among species. Oaks, hickory, black locust and sassafras, subordinate species in the understory before the burn, increased in numbers. Mountain laurel, the dominant species before the burn, initially decreased in the understory, but sprouted prolifically and returned to its pre-burn density and basal area levels ten years after the fire. We found that burning stimulated production of berries (black huckleberry, blackberry [*Rubus* spp.], and blueberry) and grasses, which are important sources of forage for wildlife, and other researchers have reported similar findings (Langdon 1981, Ducey *et al.* 1996, Keyser *et al.* 1996, Van Lear *et al.* 2004).

The effect of intense fire on oak regeneration has received less attention despite the fact that intense fires have produced the most dramatic results (Ward and Stephens 1989, Nowacki *et al.* 1992). We found that even ten years after a single event, oaks have increased their numbers in the understory, and the herbaceous layer is more diverse with a concomitant increase in non-woody growth forms.

The combination of high overstory mortality and low recruitment of pine species indicates that a single intense burn on the ridge location was not successful in restoring the pine component of this degraded pine-hardwood community. The longer term measurements were especially important in support of these observations because pitch pine regeneration was high (2381 seedlings ha^{-1} and 342 saplings ha^{-1}) immediately after the burn and many overstory pines were still alive (425 trees ha^{-1}) two years post-fire. Ten years after the burn, we found no new pine seedlings and fewer pine in the understory (82 saplings ha^{-1}) and overstory (51 trees ha^{-1}) than before the prescribed fire.

Other researchers have suggested that ridge-top pine systems, particularly Table Mountain pine, do not require high intensity (or stand replacement) fires to regenerate (Waldrop *et al.* 2003, Brose and Waldrop 2006). For example, Brose and Waldrop (2006) reported that ridge-top pine systems historically had frequent low intensity fires with episodic high intensity burns. Frequent, low intensity prescribed burns could reduce fire-sensitive species and slowly reduce highly flammable fuels (i.e., pine needles and twigs), while maintaining pine and oak in the overstory.

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