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Vegetation dynamics vary across topographic and fire severity gradients following prescribed burning in Great Smoky Mountains National Park

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ABSTRACT

Fire exclusion in the United States over the last century has had major impacts on forest ecosystems and landscapes. Out of a desire to reverse or mitigate the impacts of fire exclusion, some managers conduct prescribed fires meant to mimic the historic ecological role of fire and restore ecosystem properties. In the Southern Appalachians, fire exclusion in pine- and oak-dominated xeric ridge forests has allowed fire-sensitive hardwood species to establish, filling in the canopy and creating shady, moist conditions that are unfavorable for reproduction of fire-dependent pines and oaks. Managers of natural areas use prescribed fire to restore pine and oak dominance, promote pine and oak regeneration, and reduce stand densities. Here, we use multivariate analysis of monitoring data collected before and after 21 fires over 16 years in fire-suppressed xeric pine-oak forests in the Great Smoky Mountains National Park to assess how community composition and structure change after prescribed fire, to what degree changes after fire persist over time, and how the impacts of prescribed fire vary with fire severity and site environment. Fire consistently reduces stand density and shifts plots towards lower shrub cover and higher herbaceous cover. On the other hand, compositional shifts, i.e. changes in relative abundances of species, were highly variable in both magnitude and direction. Fire severity, measured as total fuel reduction and litter and duff reduction, was important for predicting the magnitude of change after fire. The magnitude of fire effects also varied with elevation, likely reflecting variation in local moisture conditions. Our results indicate that while fires do reduce stand density, they have not yet been successful in consistently restoring pine and oak dominance in the canopy. Restoring pine- and oak-dominance in xeric ridge forests in the Southern Appalachians will thus require extended management focus with flexible, adaptive, long-term planning and continued monitoring and research.

1. Introduction

Disruption of historic fire regimes, i.e. changes in the frequency, extent, timing, and intensity of fires, can have major impacts on the structure, composition, and function of forest ecosystems. The extent of burning in the United States has declined precipitously since the early 20th century, due to active fire exclusion (Tilman et al., 2000), with major consequences for North American ecosystems. Fire exclusion alters landscape structure (Baker, 1992), species composition (Parsons and DeBenedetti, 1979; Gilliam and Platt, 1999), forest structure, and carbon dynamics (North et al., 2009; Tilman et al., 2000). Out of a desire to reverse or mitigate the impacts of fire exclusion, many land managers conduct prescribed fires meant to mimic the historic ecological role of fire and restore pre-exclusion ecosystem properties. However, long-term studies of the impacts of reintroducing fire in fire-suppressed ecosystems are few, and the long-term impacts of restoring prescribed fire and how these impacts vary depending on when and where prescribed fires are conducted is not well known.

Fire exclusion in the eastern US can drive mesophication, a positive feedback in which fire-prone, open-canopy forests undergo succession towards dense, closed-canopy forests with moist microclimatic conditions and more compact, less flammable leaf litter: unfavorable conditions for fire ignition and spread (Nowacki and Abrams, 2008). Mesophication occurs more quickly at wetter sites

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where fire-sensitive mesophytic species can establish and grow more quickly than on more xeric sites. This can transform formerly fire-dependent communities to an alternate stable state in which restoration of previous forest structure and composition may be exceedingly difficult (Nowacki and Abrams, 2008). While prescribed fire may help slow or reverse the process of mesophication, doing so becomes increasingly difficult as mesophication progresses (Abrams, 2005). Thus, identifying conditions under which prescribed fire will be most effective at restoring fire-dependent communities and places where fire is most urgently needed to slow mesophication is important for making the best use of limited fire management resources and to best conserve the fire-dependent forests of the eastern US.

Mesophication occurs in the xeric pine-oak forests of the Southern Appalachians (Flatley et al., 2015). Here, fire-dependent forest communities dominated by yellow pines and oaks are found on xeric south and southwest facing slopes and ridgetops at mid-elevations (Whittaker, 1956; Jenkins, 2007). These forests were historically dominated by yellow pines (*Pinus* subgenus *pinus*) such as pitch pine (*P. rigida*), Virginia pine (*P. virginiana*), shortleaf pine (*P. echinata*), and Table Mountain pine (*P. pungens*), and by oaks, such as scarlet oak (*Quercus coccinea*), chestnut oak (*Quercus montana*), white oak (*Quercus alba*), black oak (*Quercus velutina*), and southern red oak (*Quercus falcata*). The dominant pine and oak species display adaptations to fire, such as thick bark and the ability to resprout after fire (Harmon, 1984). The seedlings of these species are also more successful after fires have altered light and seedbed conditions. Oaks have hypogeal germination, which places seedlings' root collar and dormant buds deeper in the soil than competitors with epigeal germination, and may enhance post-fire survival relative to other hardwoods (Brose and Van Lear, 1998; Brose et al., 2005). The yellow pine species require high light conditions and shallow litter and duff for germination and the oaks are moderately shade intolerant and germinate well on recently burned substrate (Zobel, 1969; Williams and Johnson, 1992; Brose et al., 2001; Brose and Waldrop, 2006; Waldrop and Brose, 1999). Table mountain pine has serotinous cones (Zobel, 1969; Barden, 1978), as does pitch pine in parts of its range (Ledig and Fryer, 1972; Givnish, 1981).

Prior to exclusion, frequent, low-intensity surface fires occurred at approximately 3–13 year intervals (Harmon, 1982; White, 1987; Aldrich et al., 2010; Feathers, 2010; Flatley et al., 2013). These fires maintained open, park-like stands with a grass and forb-dominated understory and shallow litter and duff layers (Harrod et al., 1998; Lafon et al., 2007). Occasional severe fires often followed a southern pine beetle (*Dendroctonus frontalis*) outbreak, ice storm, or other disturbance (White, 1987; Lafon and Kutac, 2003). High severity fires opened up the canopy, increased light availability, reduced the litter and duff layers, and promoted episodes of pine recruitment (Harrod et al., 2000; Wimberly and Reilly, 2007; Jenkins et al., 2011). Lightning fires can occur in the Southern Appalachians, (Harmon, 1982; Cohen et al., 2007) but the majority of historical fires that shaped pre-exclusion stands are believed to have been anthropogenic. Native Americans used low-intensity surface fire to maintain hunting and gathering grounds (Delcourt and Delcourt, 1997, 1998; Brose et al., 2001), and early European settlers used fire to improve common grazing lands and conditions for hunting and gathering, or for pest and disease prevention (Jurgelski, 2008; Aldrich et al., 2014).

Fire exclusion and changes in human fire-use patterns since the early 20th century have greatly changed structure and composition in xeric pine-oak forests (Harmon, 1982; Harrod et al., 1998). In the absence of frequent fire, fire-sensitive species such as red maple (*Acer rubrum*), blackgum (*Nyssa sylvatica*), yellow poplar (*Liriodendron Tulipifera*), and white pine (*Pinus strobus*) can grow large enough to resist fire (Harmon, 1984). These trees fill in the canopy and create shady, moist conditions that are conducive to their own reproduction and unfavorable for regeneration of fire-dependent species (Harrod and White, 1999). Fire exclusion has led to declines in the abundance of yellow pines and oaks and loss of landscape diversity across the Southern Appalachians (Harrod et al., 1998, 2000; Brose and Waldrop, 2006). Deep litter and duff layers have accumulated, and conditions have become shady and moist so that the occasional unintentional fire is not intense enough or large enough to reduce the litter and duff, kill back fire sensitive species, and promote pine or oak regeneration (Vose et al., 1995; Harrod et al., 1998). As a result, management agencies such as the National Park Service and US Forest Service have begun to use prescribed fire to restore pre-exclusion conditions.

These efforts have had mixed success. Elliott et al. (1999) found that while *Pinus rigida* seedlings were abundant after a prescribed fire in Nantahala National Forest, North Carolina, most died within two years after fire and ultimately, *P. rigida* seedling density was less two years after prescribed fire than before. This may have been due to competition for light from shrubs like mountain laurel (*Kalmia latifolia*), which resprouted vigorously after fire. Welch et al. (2000) found *P. rigida* and *Pinus pungens* seedlings present after low intensity prescribed fire. However, shrubs and hardwoods were not exposed to lethal temperatures, and resprouted to such an extent that understory density after fire was twice that before fire within a year after prescribed fire. Jenkins et al. (2011) found that below a certain threshold of fire severity, yellow pine seedlings were not observed following prescribed fire in the Great Smoky Mountains National Park (GSMNP). These studies demonstrate that to successfully promote pine regeneration, prescribed fire must open the canopy, reduce litter and duff, and expose competitors to lethal temperatures. They also suggest that effects of prescribed fire observed in the short term may diminish over time. Because data for longer than two years after a prescribed fire are often unavailable, evaluating the effectiveness of prescribed fire at achieving management goals in the long-term is difficult.

Prescribed fire or a particular prescribed fire regime can have different effects depending on the environment, climate, or history of a given location. In wetter sites where mesophication is hypothesized to proceed more quickly (Abrams, 2005; Nowacki and Abrams, 2008), low- to medium-severity prescribed fire may not cause mortality of fire-sensitive species if they have grown large enough to resist fire. The effects of low- to medium-severity fire may be greater at drier sites if fire-sensitive species are still present in the smaller size classes. The most xeric sites with rocky, thin soil may not require prescribed fire at all to maintain populations of *P. rigida* or *P. pungens* (Williams, 1998; Barden, 2000), though these sites are relatively uncommon in GSMNP. Many studies of prescribed fire in the Southern Appalachians examine the effects of only one fire and do not compare impacts across a gradient of environmental, topographical, and fire conditions. Better understanding where to focus prescribed fire efforts requires examining the effects of multiple fires across an environmental gradient.

In this study, we use long-term fire effects monitoring data from GSMNP spanning 16 years and 21 fires to address the following questions:

(1) How does introducing prescribed fire to a long-unburned forest affect adult tree community structure and composition?
(2) Do these changes persist over time?
(3) Do the magnitude of change and the degree to which changes are maintained over time vary with site environment conditions and/or fire severity?