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Changes in stand structure and tree vigor with repeated prescribed fire in an Appalachian hardwood forest

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ABSTRACT

Without large scale disturbances to alter forest structure and open the canopy, historically oak-dominated forests of the central and Appalachian hardwood regions of eastern North America are shifting to dominance by shade-tolerant, 'mesophytic' species. In response, prescribed fire is applied with increasing frequency and spatial extent to decrease non-oak species and promote dominance of oak species. However, relatively few studies have examined impacts of repeated fire to forest structure and tree vigor across multiple years and varied terrain. In this study, we examined tree vigor, tree mortality, and stand structure in response to different burn treatments: Frequent (burned 4 times in eight years), Less Frequent (burned 2 times in eight years), and Fire-Excluded. We hypothesized that fire-driven decreases in stem density and basal area would be greatest for small size classes, especially of shade-tolerant species on drier landscape positions, and would increase with burn frequency and fire temperature. We expected trees surviving fire to exhibit increased crown vigor over time since fire. Prescribed fire effects depended on tree size-class and landscape position. About 60% of surviving midstory trees (10–20 cm diameter at breast height (DBH)) and 25% of overstory trees ($\geqslant$20 cm DBH) on sub-xeric and intermediate landscape positions experienced crown dieback. Fire-Excluded sites had fewer trees with crown dieback (11–28% across size classes) compared to burned sites (21–87%). Throughout the duration of the study, midstory and overstory maples had significantly greater likelihood of increased crown dieback compared to oaks. Paradoxically, midstory maples had a higher survival probability than similarly-sized oaks, while overstory maples had lower survival than overstory oaks. The greatest reductions in density and basal area occurred in saplings (trees 2–10 cm DBH) and midstory trees on sub-xeric and intermediate (but not sub-mesic) landscape positions. Both Less Frequent and Frequent burning reduced density and basal area of sapling and mid-story shade-tolerant species, but also of mid-story chestnut oaks. Individual tree mortality was positively correlated with char height after the first burn regardless of burn frequency. A large and significant initial sprouting response to fire dissipated over time and with repeated burning. Future assessments of mortality and vigor of residual trees following fire are essential for evaluating the long-term effectiveness of prescribed fire management in shifting species composition away from 'mesophytic' species and toward oaks, and could help guide management choices regarding repeated prescribed burning.

1. Introduction

Upland oak ecosystems in the central and Appalachian hardwood forests of eastern North America are shifting away from oak (*Quercus* spp.) dominance. In the relative absence of large scale disturbances of the past, shade-tolerant, 'mesophytic' species (such as red maple (*Acer rubrum* L.), sugar maple (*A. saccharum* Marsh.), and blackgum (*Nyssa sylvatica* Marsh.)) are proliferating in increasingly shaded understories (Abrams, 1992; Fei et al., 2011; Nowacki and Abrams, 2008). An understanding of prehistoric (Delcourt and Delcourt, 1997; Delcourt et al., 1998; Hart et al., 2008) and historic (Hutchinson et al., 2008; McEwan et al., 2007) fire regimes in this region has emerged rapidly over the past several decades from

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archaeological, dendrochronological, and fossil pollen and charcoal records. Evidence reveals that anthropogenic ignitions dominated the sources of fire on the landscape, occurred at varying intervals over the past 4000 years, and likely helped to shape forests in myriad ways (Delcourt and Delcourt, 1998). While the national policy of fire suppression since the 1930s has undoubtedly contributed to these changes in forest species composition and forest structure, it is increasingly apparent that the history of fire use and suppression across the landscape is insufficient both for explaining contemporary forest species composition and structure and for understanding past changes. What is emerging is a strong sense of the importance of multiple interacting disturbance agents and ecosystem drivers (*sensu* McEwan et al., 2011) that potentially include climate variability (Buchanan and Hart, 2012; McEwan et al., 2011), changing human uses of the landscape (Guyette et al., 2002), and impacts of other organisms, such as the passenger pigeon (Ellsworth and McComb, 2003), white-tailed deer and other herbivores (McEwan et al., 2011), and chestnut blight (Keever, 1953; Woods and Shanks, 1959).

Nonetheless, in response to documented shifts in long-term forest stand structure and species composition and the apparent primacy of fire as a disturbance agent, prescribed fire has been incorporated into Land and Resource Management Plans (USDA Forest Service Daniel Boone National Forest, 2005; USDA Forest Service Mark Twain National Forest, 2005; USDA Forest Service Ozark-St. Francis National Forests, 2005) throughout the region to address the restoration of oak-dominated ecosystems (Arthur et al., 2012; Yaussy et al., 2008). Yet, it is proving difficult to discern the potential for prescribed fire, applied to contemporary forests, to shift species composition and stand structure in a manner that achieves forest management goals for a more open canopy structure with lower densities of fire-sensitive and shade-tolerant species. Many stated objectives for prescribed burning, such as increased oak regeneration, require alterations to stand structure including reduced stem density and basal area. Management to achieve such objectives could, of course, incorporate forest thinning targeted at shade-tolerant, fire-sensitive species, but one of the challenges of such management is that in eastern forests, the sprouting response to top-kill is prolific, thus requiring herbicide application following cutting. In an effort to treat large areas with limited budgets, and operating on knowledge of the prehistoric and historic roles of fires on the landscape, fire is often the tool of choice, albeit one that requires repeated application and significant refinement (Arthur et al., 2012; Brose et al., 2013).

Over the past two decades, many studies have focused on the effects of prescribed fire on stand structure, species composition, and oak regeneration in central and Appalachian hardwood forests and surrounding region, with somewhat mixed results. Several studies in New York (McGee et al., 1995), Georgia (Loftis, 1990), Connecticut (Ducey et al., 1996), and North Carolina (Elliott et al., 1999) have shown reduced importance value, survival, or density of oak following a single, low-intensity prescribed fire and increased competitive status of mesophytic species like red maple, American beech (*Fagus grandifolia* Ehrh.), and black birch (*Betula lenta* L.). In Ohio (Hutchinson et al., 2005, 2012a), Kentucky (Alexander et al., 2008; Blankenship and Arthur, 2006; Green et al., 2010), and Georgia (Loftis, 1990), studies have found differing effects of prescribed fire on oak seedling success following fire-driven reductions in stem density. With this focus on the success of oak regeneration in response to prescribed fire, several studies have measured longer-term effects of multiple fires on stand structure (Barnes and Van Lear, 1998; Blankenship and Arthur, 2006; Burton et al., 2010; Fan et al., 2012; Hutchinson et al., 2012b; Signell et al., 2005), again with somewhat varied results that likely reflect variability in geography and species composition, as well as nuances of burn behavior. Measures of tree vigor are rarely included in these studies, yet data stemming from such measures may be key to how future stand dynamics will unfold, especially if fires lead to declined vigor, or even mortality, of residual, seed-producing overstory oaks.

This study examined the effects of prescribed fire implemented over eight years at differing frequencies on crown dieback (measured using crown dieback classes, and changes in crown dieback classes), tree mortality, stand structure, species composition, and sprouting response, as well as the relationship between fire temperatures and char height, mortality, and crown dieback class. We hypothesized (H1) that prescribed burning would impact stand structure and species composition, and that these effects would be greater on sub-xeric and intermediate sites compared to sub-mesic sites because of greater flammability and burn severity on drier sites. We also expected greater impacts to maples versus oaks after the first fire (H1a), and that the initial pulse of tree mortality after the first fire would cause the greatest change to stand structure (H1b). We further hypothesized (H2) that char height and fire temperature would be positively correlated with tree mortality and negatively correlated with the vigor (measured using crown dieback classes) of surviving trees. Additionally, we hypothesized (H3) that prescribed burning would initially increase sprouting response, but that subsequent fires would lead to fewer surviving sprouts. Finally, we hypothesized (H4) that in subsequent years, surviving trees would recover from the effects of fire, as measured by increasing crown dieback class, based on the assumption that lower stem density and basal area would allow for increased access to limited availability of soil moisture, light and nutrients.

2. Materials and methods

2.1. Study area

This study was conducted on the Cumberland Plateau in eastern Kentucky, in the Cumberland Ranger District of the Daniel Boone National Forest (DBNF) in the Low Hills Belt (Braun, 1950). Climate is humid, temperate and continental. Mean annual air temperature is 12.8 °C, with cool winters (January mean daily temperature is 0.5 °C) and warm summers (July mean daily temperature is 24 °C; Foster and Conner, 2001). Annual mean precipitation of 122 cm is distributed fairly evenly throughout the year (Foster and Conner, 2001). The study area encompasses varied topographic terrain and aspect, with elevations ranging from 260 to 360 m and slopes ranging from 0% to 75% (median 45%). Steep slopes and unglaciated terrain lead to variation in topography from shallow coves to exposed ridges, which influence soil moisture conditions. Soils are variable in depth and texture, and are classified as Typic Hapludults, Typic Hapludalfs, Ultic Hapludalfs, and Typic Dystrochrepts (Avers, 1974).

Prior to burning, the study sites were second-growth forests dominated by oaks and hickories (*Carya* spp.) in the midstory (stems 10–20 cm diameter at breast height (DBH)) and overstory (stems $\geqslant$ 20 cm DBH). The forests regenerated since extensive logging and range in age from 80 to 110 years, on site indices ranging from SI 15 to 34 m based on white oak (*Q. alba* L.), base year 50. The sapling stratum (stems 2–10 cm DBH) was dominated by red and sugar maple, downy serviceberry (*Amelanchier arborea* (Michx. f.) Fern., blackgum, and sourwood (*Oxydendrum arboreum* (L.) DC.). Stem density and basal area of saplings (2–10 cm DBH), midstory (10–20 cm DBH), and overstory ($\geqslant$20 cm DBH) trees were similar among burn treatments and landscape positions (Tables 1 and 2). Density of saplings averaged 899 stems ha^{-1}. Tree densities of midstory and overstory stems were similar, averaging 249 and 211 stems ha^{-1}, respectively, across all landscape positions. Basal area averaged 2 m^2 ha^{-1} for saplings, 4 m^2 ha^{-1} for midstory, and