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Alterations to the fuel bed after single and repeated prescribed fires in an Appalachian hardwood forest

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ABSTRACT

To manage upland oak forests across the central and southern Appalachian mountain and plateau regions, prescribed fire is applied more frequently and across larger areas than in the recent past. The often stated objective is to reduce fuels, but there is a paucity of information on the impacts of repeated burning on fuels, including woody materials and the soil organic layer. These are complex components of forest ecosystems with significant impacts on nutrient and carbon cycling, forest successional dynamics, and soil protection from loss via erosion. Thus, understanding fuel bed response to prescribed fire is essential for predicting future forest function. Using study sites distributed across a range of landscape positions in the Daniel Boone National Forest on the Cumberland Plateau of eastern Kentucky, we examined changes to the fuel bed over six years in response to a single fire (burned once in six years), repeated fire (burned four times in six years), and fire-excluded treatments to determine prescribed fire impacts on fuel loads and mineral soil exposure. Prior to burning, fuel loads were generally similar among landscape positions, although the duff layer was lowest on sub-mesic and greatest on sub-xeric positions. A single fire reduced duff depth by 50%, whereas repeated burning led to depth reductions of > 60%. Repeated burning also significantly increased mineral soil exposure (25%) compared to single burn and fire-excluded (2–4%) treatments, with the greatest effects on sub-mesic and intermediate landscape positions. Repeated burning significantly reduced fine woody (1-h) fuels, but only after three burns, whereas fine fuel mass on sites burned once was similar to those where fire was excluded. There were no statistically significant effects of burning on large woody fuels (100- and 1000-h fuels). Overall, the primary impact of prescribed fire on the fuel bed was to consume the organic horizon and expose mineral soil, which has the potential to reduce fuel continuity for subsequent burns. Fire behavior in this region is driven primarily by fine fuels (litter and duff) and fuel continuity, both of which recover in relatively short periods of one to several years. Reduction of woody fuels is more intractable under a prescribed fire regime.

1. Introduction

Forest ecosystem function is strongly linked to the accumulation of dead organic matter both in the soil organic horizon and woody materials. Dead organic matter serves as the substrate for the detrital food web, storage and cycling of carbon (C) and nutrients, seedbed for plant germination and establishment, habitat for plant roots and wildlife, soil protection from surface runoff, and fuel for fires (Certini, 2005). Fluctuations in the pools of dead organic matter are controlled by a complex suite of factors, from highly stochastic disturbance events like ice and wind storms that can contribute large volumes of woody materials quickly, to the ongoing processes affecting organic matter accumulation, such as decomposition rates, forest productivity, and vegetation species composition (Kalbitz et al., 2000, Vesterdal et al., 2013).

Throughout much of North America, fire is a frequent disturbance agent that serves as an important regulator of dead organic matter. Frequent fire can reduce soil C pools by combusting litter and reducing forest floor depth (Boerner et al., 2009; Royse et al., 2010), but frequent burning may also increase litter C:N (nitrogen) through changes in species composition and/or in response to decreased soil N availability, potentially mitigating such losses through reduced decomposition rates (Hernandez and Hobbie, 2008). Alternatively, long fire-free intervals resulting from fire suppression can increase dominance of tree species with fast decomposition rates, potentially lowering soil C accumulation rates (Alexander and Arthur, 2014; Knoepp et al., 2009).

In upland oak forests of the central and southern Appalachian

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regions, there is growing evidence that the historic fire regime was significantly altered or even entirely suppressed following Euro-American settlement (Flatley et al., 2013; Guyette et al., 2002; Nowacki and Abrams, 2008). While fire suppression during Euro-American settlement has been posited to have increased woody fuel accumulation with potential for increased fire activity (Spetich et al., 1999), others have demonstrated a lack of evidence for this assertion (Polo et al., 2013). Significant impacts of fire suppression to forest structure and species composition include increased dominance of mesophytic species, i.e., species that may reduce forest flammability by creating cool, moist fuels with lower abundance (Nowacki and Abrams, 2008). Recent findings suggest that key mesophytic species, such as red maple (*Acer rubrum* L.), increase litter moisture (Kreye et al., 2013), increase leaf litter decomposition rates (Alexander and Arthur, 2014), and alter precipitation distribution (Alexander and Arthur, 2010), which taken together, could reduce forest flammability. This emerging understanding of the role of fire in the central and southern Appalachian regions has led to increased use of prescribed fire as a component of forest management. The broad goals for forest management with prescribed fire in this region contributed to the motivation for this research on woody fuels, which was part of a larger study that examined the use of prescribed fire at 'frequent' and 'less frequent' intervals and the subsequent changes to stand structure and tree vigor (Arthur et al., 2015), survival and growth of upland oak and competitor seedlings (Alexander et al., 2008; Alexander and Arthur, 2009), establishment of new oak seedlings after burning (Royse et al., 2010), and response of understory vegetation (Keyser et al., 2017).

There are several reasons we need more information about fuels and fire in Appalachian hardwood forests. First, a concern about fuel accumulation and the potential for unplanned fire has been one justification for the frequent and repeated use of prescribed fire across the central and Appalachian hardwood forest regions (USDA Forest Service Mark Twain National Forest, 2005; Waldrop et al., 2016). A related knowledge gap is how prescribed fire alters the fuel bed and whether this influences the potential for wildfire or wildfire behavior. Second, surface organic matter serves an important role for various ecosystem functions, altering C storage, water and nutrient availability, and increasing invasibility. With more planned burning on the landscape (Arthur et al., 2012) and potential for greater unplanned burning if global temperatures rise as predicted (Liu et al., 2013), there is a need to understand how prescribed fire alters the organic horizon from an ecosystem perspective. Finally, there are relatively few studies quantifying how repeated prescribed fire alters the fuel bed, including whether prescribed fire has differential impacts to the fuel layer in different landscape positions. Most studies that have examined the effects of prescribed fire on fuel-loading in this region have been based on short-term studies with one or two burns (Chiang et al., 2008; Graham and McCarthy, 2006; Hubbard et al., 2004; Loucks et al., 2008); only a few have reported on long-term effects of repeated burning (Neill et al., 2007; Polo et al., 2013; Waldrop et al., 2016).

We used a replicated study of prescribed fire implemented as US Forest Service management burns, across topographically varied terrain within the Cumberland Plateau of eastern Kentucky to examine the effects of single versus repeated prescribed fire on forest floor and woody fuels. We previously reported that single and repeated prescribed fires reduced stem density and basal area, but to a greater extent on sub-xeric and intermediate landscape positions compared to sub-mesic (Arthur et al., 2015). Further, we found greater char height, tree mortality, and lower crown vigor on sub-xeric and intermediate sites compared to sub-mesic landscape positions (Arthur et al., 2015). We have also previously reported on the effects of a single fire on fuels, demonstrating that fire significantly reduced litter mass and depth, both of which recovered to levels statistically indistinguishable from pre-burn measurements 10 months post-burn (Loucks et al., 2008). The burn had no significant effect on other fuel components (Loucks et al., 2008).

Here, we extend this previous research for three additional prescribed fires to determine the effects of repeated fire on dead woody fuels and the soil organic horizon. We asked two primary questions about prescribed fires and fuels in an Appalachian hardwood forest: (1) Do single and repeated prescribed fires alter forest floor and woody fuel mass, and if so, do the effects differ by landscape position?; and, (2) Do single and/or repeated fires lead to increased mineral soil exposure?

2. Methods

2.1. Study area

Study sites were located in the Cumberland Ranger District of the Daniel Boone National Forest (DBNF) on the Cumberland Plateau in eastern Kentucky. The region's climate is humid, temperate and continental. Winters are cool with mean daily temperature in January of 0.5 °C, and summers are warm with mean daily temperature in July of 24 °C. Annual mean air temperature is 12.8 °C (Foster and Conner, 2001). Precipitation is distributed fairly evenly throughout the year with an annual mean of 122 cm (Foster and Conner, 2001). The terrain of the study area varied in topography and aspect with elevations ranging from 260 to 360 m and slopes ranging from 0 to 75% slope (median 45%). Topographical variation ranged from shallow coves to exposed ridges, including steep slopes and unglaciated terrain, which influences soil moisture conditions (Jones, 2005). Soils are variable in depth and texture and classified as Typic Hapludults, Typic Hapludalfs, Ultic Hapludalfs, and Typic Dystrochrepts, (Avers, 1974).

The study sites were second-growth forests (80–110 years of age since extensive logging) dominated by upland oaks (*Quercus* spp.) and hickories (*Carya* spp.) in the overstory (stems ≥10 cm DBH), with site index (SI) of 50–110. Red and sugar maple (*A. saccharum* Marsh.) dominated the midstory (2–10 cm DBH) along with downy serviceberry (*Amelanchier arborea* Michx. F.), black gum (*Nyssa sylvatica* Marsh.), and sourwood (*Oxydendrum arboreum* L.). The sites had not been burned by wildfire or prescribed fire in the last 30+ years prior to this study (Loucks et al., 2008). Due to a lack of live fuels in this closed-canopy forest ecosystem, fuel measurements included only dead fuels; live fuels such as grasses and vines, though occasionally present on the site, occur only in isolated circumstances and with low stature.

2.2. Experimental design

In 2002, three study sites (Buck Creek, Chestnut Cliffs, and Wolf Pen), each ~200 to 300 ha in area, were established within an 18 km^2 area. Each study site was subdivided into three treatments: repeated burn, to which prescribed fire was applied in 2003, 2004, 2006, and 2008; a single burn, to which prescribed fire was applied in 2003; and fire-excluded. Using a stratified-random sampling scheme designed to select plots across the varied terrain of each area, 8–12 study plots were located within each treatment-site combination for a total of 92 plots. Plots were 10 m × 40 m, laid out parallel to the topographic contour. Plots were assigned a landscape position (sub-xeric, intermediate, or sub-mesic) using a classification system based on tree species composition (McNab et al., 2007; McNab and Loftis, 2013). Five fire-excluded plots in one study site (Wolf Pen) burned accidentally in an unplanned fire in December 2006, leaving 26 fire-excluded plots beginning with measurements made in 2007 (Table 1).

2.3. Prescribed fires and temperature measurements

USDA Forest Service personnel conducted the prescribed fires according to established prescription parameters (USDA Forest Service, 2011). Fires were typically ignited by hand using drip torches, although in 2003, two of the three sites were ignited aerially (Table 2). Burns were conducted between March 24th and April 16th, when air temperatures were between 20–27 °C, and relative humidity was between