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Soil properties in fire-consumed log burnout openings in a Missouri oak savanna

C.C. Rhoades[a,*], A.J. Meier[b,1], A.J. Rebertus[c,2]

[a]*USDA Forest Service, Rocky Mountain Research Station, 240 W. Prospect, Fort Collins, CO 80526, USA*
[b]*Department of Biology, Western Kentucky University, Bowling Green, KY 42101, USA*
[c]*Biology Department, Northern Michigan University, Marquette, MI 49855, USA*

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Abstract

Downed logs are known to increase species diversity in many forest ecosystems by increasing resource and structural complexity and by altering fire behavior in fire-prone ecosystems. In a frequently burned oak savanna in central Missouri, combustion of downed logs formed patches that have remained free of herbaceous vegetation for more than 3 years. To assess the influence of "log burnouts" on soil conditions we compared soil chemical, biological and physical properties in log burnout zones and beneath surrounding herbaceous vegetation. Soil pH and extractable soil NO_3^-, P, K^+ and Ca^{2+} were all higher in the log burnouts compared to adjacent soil. There was no difference in total soil N or extractable NH_4^+. An index of plant N availability was lower and the soil C:N ratio was higher in the burnout patches, though the magnitudes of these reductions do not explain the persistence of the bare patches. We suspect that following log combustion degraded soil aggregate structure and decreased soil porosity alters soil water availability and restricts plant colonization into the log burnouts areas. The modified soil conditions associated with fire-consumed coarse woody debris may have a long-term influence on herbaceous species diversity and spatial distribution in fire-maintained oak savannas.

Keywords: Coarse woody debris; Soil nitrogen cycling; Fire behavior; Prescribed fire; Missouri Ozarks

1. Introduction

Downed logs are known to increase the biodiversity of coniferous and deciduous forest ecosystems by increasing resource and structural complexity of the forest floor (Harmon et al., 1986; Hansen et al., 1991; McMim and Crossley, 1996; Greenberg, 2002; Lohr et al., 2002). Downed coarse woody debris (CWD) represents a reservoir of nutrients, moisture, seed and fungal spores (Amaranthus et al., 1994; Nakasone, 1996; Hart, 1999), and it provides habitat for taxonomically diverse fauna (Bull et al., 1997). Certain forest species require downed logs as substrate for seedling germination (Harmon et al., 1986; Harmon and Franklin, 1989). In fire-prone forest ecosystems, CWD can greatly alter fire behavior and intensity as compared to smaller or lighter fuel types (Pyne et al., 1996). Management activities intended to increase forest biodiversity and to maintain diverse ecosystem processes have led natural resource agencies to develop

* Corresponding author. Tel.: +1-970-498-1250.
E-mail addresses: crhoades@fs.fed.us (C.C. Rhoades), albert.meier@wku.edu (A.J. Meier), arebertu@nmu.edu (A.J. Rebertus).
[1] Tel.: +1-270-745-6525.
[2] Tel.: +1-906-227-2351.

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guidelines and policies to quantify and manipulate CWD inventories (Graham et al., 1994; Shifley and Brookshire, 2000).

In midwestern North American oak savannas, fire was the dominant disturbance agent that historically influenced vegetation at the stand scale (Nuzzo, 1986; McPherson, 1997; Johnson et al., 2002) and at broader landscape and regional scales (Fralish et al., 1999; Batek et al., 1999). Frequent low- to moderate-intensity fires maintained the open, park-like nature of savanna overstory (Anderson and Brown, 1983) and the abundance and diversity of herbaceous species (Tester, 1989) by slowing recruitment of hardwood seedlings (Packard and Mutel, 1997; Peterson and Reich, 2001).

Within stands, the discontinuous savanna overstory generates complex, overlapping gradients of light, moisture and soil nutrients and contributes to the high species diversity of the herbaceous layer (Ko and Reich, 1993; Bowles and McBride, 1998; Anderson and Bowles, 1999). Modified soil and abiotic conditions beneath the canopies of savanna trees represent resource ‘‘islands’’ where herbaceous production and species composition differ from open savanna (Belsky et al., 1989; Ko and Reich, 1993). Conversely, canopy openings formed by intense fire, wind or ice damage (Rebertus et al., 1997; Rebertus and Meier, 2001) also alter soil and abiotic resources (Belsky and Canham, 1994), herb layer productivity and woody species regeneration (Rebertus and Burns, 1997).

CWD, in conjunction with fire, may influence soil resources and species distribution patterns in oak savannas at the microtopographic scale (i.e. 1–10 m). In a frequently burned Missouri oak savanna, bare patches that formed beneath fire-consumed downed tree boles were observed scattered through the dense herbaceous layer (Fig. 1; Rebertus and Burns, 1997). Similar ‘‘log shadows’’ have been described following stand-replacing fire in Wyoming lodgepole pine forest (Tinker and Knight, 2000). Although CWD is known to influence soil resources and species distribution patterns in both eastern (McMim and Crossley, 1996; Greenberg, 2002; Lohr et al., 2002) and western North American forest types (Harmon et al., 1986; Harmon and Franklin, 1989), the scarcity of functionally intact oak savanna (Nuzzo, 1986; McCarty, 1998; Heikens, 1999) has prevented assessment of similar patterns in these species-rich Midwestern communities.

Fig. 1. Log burnout patch at AB Savanna, Camden County, Missouri.

This study examines the influence of fire-consumed CWD on oak savanna soil properties. We hypothesize that persistence of the log burnouts relates to alterations in soil properties and nutrient pools that originated during log combustion and have endured since then. Log burnout patches were compared to adjacent grass-dominated savanna in order to make a preliminary assessment of the relative importance of chemical and physical soil properties in maintaining the bare openings.

2. Methods

2.1. Site description

AB Savanna is a 15 ha, southwest-facing, chert savanna (Nelson, 1987) located in the Osage-Gasconade Hills of the Salem Plateau, Camden County, Missouri (39°N; 92°W). The savannas, glades and dry forest vegetation of the area occur on soils formed upon hillslope sediments and residuum derived from dolomite bedrock of the Ordovician Gasconade formation. These soils are very cherty silt loams classified as very fine, mixed mesic Typic Hapludalfs of the Niangua-Bardley complex (Wolf, 1994).

The overstory vegetation is dominated by post oak, black oak, and white oak (*Quercus stellata* Wang., *Q. velutina* Lam., *Q. alba* L.; Rebertus and Burns, 1997; Jenkins, 1997). The oldest trees on site are 340+-year-old post oaks. More than 300 plant species have been identified in the herbaceous layer of AB (Rebertus and Burns, 1997) and nearby savannas (McCarty, 1998). The dominant grasses include *Sorghastrum nutans*, *Andropogon gerardii*, and *Schizachyrium scoparium*. Common forbs include *Baptisia bracteata* var. *leucopahea*, *Liatris aspera*, *L. squarrosa*, *Ceanothus americanus*, *Tephrosia virginiana*, and *Amorpha canescens*. Semi-annual fires have been ignited by local residents since settlement in the 1820s. Based on fire scars from 82 trees, it has been estimated that the mean fire interval between 1714 and 1995 was 5.3 years (Jenkins and Rebertus, unpublished data).

Log burnout patches were found on 12 out of 26 randomly located 0.1 ha circular plots (46% occurrence; Rebertus and Burns, 1997). The devegetated zones averaged 3.1 m long by 1.4 m wide; maximum dimensions were 7.2 m in length and 5.2 m in width ($n = 10$). Log burnouts covered 0.22% of the study area (mean = 22 m^2 ha^{-1}). According to local residents, the majority of the log burnouts were created during March 1994 when logs smoldered for several days following an especially hot human-ignited fire; a few logs may also have been combusted during the spring of 1997 (Jenkins and Rebertus, unpublished data). In July 2000, at the time of sampling, charred stumps and stump holes remained, but there were few charcoal or log fragments and no surface discoloration within the burnout openings. At that time, we were unable to determine the specific age of individual burnouts patches; we assume that the majority of the log burnouts originated 6 years prior to sampling and that they are no less than 3 years old.

To assess soil conditions within the AB Savanna log burnouts we sampled paired burnout openings and adjacent grassland. Within the log burnouts, two 6 cm diameter subsamples located 1–2 m apart, were collected from the upper 10 cm of mineral soil using a slide-hammer soil corer (Giddings Equipment, Ft. Collins, CO) and then composited. Visible influence of the log burnouts on surface soil properties and herbaceous species composition or biomass extended less than 1 m from the burnout openings, so we collected grassland subsamples 2 m from the perimeter of each log burnout. Field-moist cores were broken apart and roots were removed by hand and soils were air-dried for 2 weeks at 24 °C. Air-dry soils were then passed through a 2 mm sieve to remove coarse fragments. Roots were washed to remove attached soil, dried for 48 h at 60 °C and weighed.

To assay plant-available soil N we measured both instantaneous pools of mineral N (KCl-extractable NO_3^- and NH_4^+) and an index of N availability (anaerobic incubation) that estimates the N contained within and released from microbial biomass and labile soil organic matter (Binkley and Hart, 1989). Nitrate and ammonium pools were extracted from 10 g subsamples with 50 ml of 1 M KCl, shaken for 1 h, filtered and analyzed by colorimetric spectrophotometry (Bundy and Meisinger, 1994). To index plant-available soil N a 20 g subsample of air-dry soil was waterlogged with 50 ml of deionized water and incubated at 40 °C for 7 days (Waring and Bremner, 1964; Bundy and Meisinger, 1994). At the end of the incubation period, 50 ml of 2 M KCl was added to the waterlogged subsamples; extraction and analysis proceeded as above.

Mineral soil total C and N were analyzed by dry combustion (LECO CHN 2000). Soil pH was analyzed in a 1:1 soil to deionized water slurry after 1 h of agitation (Thomas, 1996). Exchangeable phosphorus and cations were extracted with Mehlich-III reagents (Mehlich, 1984) and analyzed by colorimetry for P and by inductively coupled plasma for K^+, Ca^{2+}, Mg^{2+}. Soil texture was measured with the Bouyoucos hydrometer method (Gee and Bauder, 1986). Bulk density of the fine fraction was estimated from the upper 10 cm depth, after subtracting the oven-dry mass (24 h at 105 °C) and volume of coarse fragments (Blake and Hartge, 1986). Bulk density values were used to convert nutrient concentrations to area-based measurements.

Differences in soil nutrient pools and physical properties between ten log burnout patches and adjacent herbaceous sample areas were analyzed using a paired *t*-test (SPSS Inc., Chicago, IL).

Table 1
Soil pH and extractable P and cations in the upper 10 cm of mineral soil at AB Savanna, Missouri (mean and S.E.)

	pH	P	K^+ (kg ha^{-1})	Ca^{2+} (kg ha^{-1})	Mg^{2+} (kg ha^{-1})
Log burnout	7.3 (0.2)	16.5 (2.9)	178.0 (29.7)	2224.1 (371.7)	206.7 (78.6)
Open grass	6.5 (0.2)	7.2 (1.6)	96.8 (11.6)	934.56 (156.2)	144.5 (37.3)
Paired *t* significance	0.005	0.004	0.008	0.000	0.149

Paired *t*-tests evaluate differences between individual log burnout patches and adjacent grassland ($n = 10$).

Table 2
Extractable soil N and total soil N and C pools and an index of N availability (0–10 cm) at AB Savanna, Missouri (mean and S.E.)

	Extractable soil N (kg N ha^{-1})			N availability index (μg N g^{-1} per 7 days)	Total N (Mg ha^{-1})	Total C (Mg ha^{-1})	C:N
	NH_4^+	NO_3^-	Sum				
Log burnout	1.2 (0.2)	0.4 (0.1)	1.6 (0.3)	20.0 (1.4)	1.2 (0.2)	22.4 (2.9)	19.1 (0.7)
Open grass	1.5 (0.2)	0.0 (0.0)	1.5 (0.2)	27.0 (3.2)	1.4 (0.1)	25.0 (2.1)	17.8 (0.4)
Paired *t* significance	0.388	0.007	0.919	0.083	0.137	0.293	0.022

Paired *t*-tests evaluate differences between individual log burnout patches and adjacent grassland ($n = 10$).

3. Results

The pH of AB Savanna surface soils ranged from 4.9 to 8.1 (6.9 average). Within the log burnouts, soil pH was 0.8 units higher than adjacent grassland soil (*t*-test, $P = 0.005$; Table 1). Extractable P, K^+, and Ca^{2+} pools in log burnouts were all twice that of the adjacent grassland (*t*-test, $P < 0.01$). Extractable Mg^{2+} in log burnouts was somewhat higher (1.4-fold greater than savanna soil), though the difference was not statistically significant (*t*-test, $P = 0.15$).

Ammonium (NH_4^+), the dominant form of mineral N in AB soils, did not differ between the burnout openings and adjacent grassland (Table 2). In contrast, log burnouts had significantly higher NO_3^- compared to adjacent areas (*t*-test, $P = 0.007$). The NO_3^- pool was near zero in savanna soils (0.02 kg N/ha), whereas it represented 25% of total inorganic N in the log burnouts. Nitrogen availability as indexed by the anaerobic incubation was 25% lower in log burnout soils (*t*-test, $P = 0.08$). Total pools of soil C and N were both slightly, but insignificantly lower within the log burnouts, but the soil C:N ratio was statistically higher in the log burnouts compared to adjacent grassland (*t*-test, $P = 0.02$). Root biomass was three-fold higher in the savanna grassland compared to the log burnouts (*t*-test, $P = 0.006$). Clay was statistically higher (*t*-test, $P = 0.03$) and sand was lower (*t*-test, $P = 0.03$) in the log burnouts (Table 3), though these differences may be of little biological significance.

4. Discussion

The soil conditions measured within the AB Savanna log burnouts are typical of soil changes

Table 3
Soil particle size density, coarse fragments and bulk density of the upper 10 cm of mineral soil at AB Savanna, Missouri (mean and S.E.)

	Sand (%)	Silt (%)	Clay (%)	Coarse fragments (%)	Bulk density (g cm^{-3})
Log burnout	34.1 (1.6)	58.8 (1.6)	7.1 (0.7)	51.0 (2.7)	1.0 (0.1)
Open grass	36.4 (1.8)	57.1 (1.7)	6.5 (0.8)	50.4 (2.8)	0.9 (0.0)
Paired *t* significance	0.034	0.082	0.029	0.834	0.506

Paired *t*-tests evaluate differences between individual log burnout patches and adjacent grassland ($n = 10$). Coarse fragments: 2 mm sieve mesh.

resulting from severe fire behavior. Heavy fuels such as CWD, logging residue (Tarrant, 1956) or deep organic matter layers (Sackett and Haase, 1992) increase fire intensity, the depth of temperature penetration into the soil and the duration of soil heating effects (DeBano et al., 1998; Giardina et al., 2000). For example, beneath a *Eucalyptus* log pile, soil temperature exceeded 300 °C at 5 cm depth 7 h after the fire was ignited (Roberts, 1965); for more than 24 h following ignition, soil temperature surpassed 100 °C to a depth of 22 cm. Under such intense fire conditions, soil heating, ash deposition or a combination of the two factors alter physical, chemical and biological soil properties (Romanya et al., 1994; Giardina et al., 2000). Similar conditions must have occurred at AB Savanna during the days that the downed logs smoldered.

Soil pH and cation nutrients commonly increase immediately following severe slash or debris burning (Covington et al., 1991; Marion et al., 1991; Bauhus et al., 1993) and the effect typically remains for one to several years. At AB Savanna significant soil changes persisted for at least 3 years following consumption of downed logs (Tables 1 and 2). Combustion of logging debris increased soil pH by 2.8 units in northwestern North American conifer forests (Tarrant, 1956) and by 3.6 units in southeastern Australia (Bauhus et al., 1993). Following low intensity slash fires, soil pH returned to within 0.5 units of original conditions within 2 years of combustion (Tarrant, 1956). In contrast, on severely burned microsites pH remained 1.2 units above unburned controls after 2 years. A similar pattern occurred in the AB Savanna log burnouts where pH was 0.8 units higher on average and as much as 1.6 units higher than the surrounding savanna soil.

Soil N availability and extractable soil ammonium also increase sharply immediately after slash fires (Covington et al., 1991; Bauhus et al., 1993) or prescribed burning (Covington and Sackett, 1992). An increase in soil nitrate often lags weeks or months after combustion as nitrifying bacteria respond to the increase in ammonium and soil pH (Fisher and Binkley, 2000). These soil N pools usually return to preburn levels 2–5 seasons after burning as plant and microbial N uptake drain these labile and scarce soil resources (Covington et al., 1991). For example, beneath slash piles in pinyon-juniper woodlands (*Juniperus monosperma* (Engelm.) Sarg. and *Pinus edulis* Engelm.), NH_4^+ increased 50-fold immediately following burning and NO_3^- grew 20-fold after 1 year; these increases in mineral N declined within 3–5 years (Covington et al., 1991). Three or more years following burning at AB Savanna, any previous effect of the fire on soil NH_4^+ had disappeared although soil NO_3^- remained elevated relative to the surrounding savanna (Table 2).

Production of mineral soil N through the microbial oxidation of soil organic matter (net mineralization and nitrification) may increase shortly after burning (Covington and Sackett, 1992; Giardina and Rhoades, 2001) and can remain elevated for months to years. However, reduced net N production along with increased N immobilization by soil microbes has also been measured where labile substrates are depleted by either individual or repeated burns (Vance and Henderson, 1984; Bell and Binkley, 1989). The decrease in N availability (anaerobic index) within the AB log burnouts may be the combined result of the slight decline in the total N pool combined with a shift in soil organic matter quality as indicated by the increased total soil C:N (Paul and Clark, 1989).

Although soil nutrient pools, N availability, C:N and acidity all differed significantly between log burnouts and adjacent savanna soils, these differences are unlikely to explain the long-term persistence of the devegetated patches. Fire also alters soil physical properties that control water infiltration and may contribute to prolonged soil effects (DeBano, 1981; Wallis and Horne, 1992). Reduced soil porosity caused by sedimentation into the log beds, destruction of soil aggregates, formation of a water repellant layer or some combination of these factors may cause a significant barrier to water infiltration and plant growth (Giovannini et al., 1988; DeBano et al., 1998).

At AB Savanna we observed no obvious indications of soil erosion, though soil aggregate disruption and sedimentation would both block soil pores and reduce the water available to colonizing plants without notable surface soil movement. Nor did we observe differences in soil wettability (i.e., water drop penetration) either in the field or during our laboratory analyses. Formation of hydrophophic layers are most common and pronounced in sandy soils, and the high silt and chert content at AB Savanna (DeBano et al., 1998) would probably hinder development of a uniform water repellant layer.

4.1. Future considerations

This study documents significant, persistent soil effects corresponding to the location of fire-consumed logs. Relative to the surrounding savanna, soils within log burnouts were enriched in plant nutrients (NO_3^-, exchangeable P, Ca^{2+}, and K^+). The reduced availability of mineral N (anaerobic index) and the increased C:N ratio were the only significant nutrient responses that might restrict plant growth into the log burnouts. However, the magnitudes of the differences are insufficient to explain the longevity of the bare patches. Further study should evaluate if altered soil porosity resulting from destruction of soil aggregates limits plant establishment on the otherwise more fertile log burnout soils. Such work will also help determine if reduced water infiltration into the burnout soils explains the persistence of elevated extractable soil nutrient pools several years following log combustion.

It is also likely that elevated soil temperatures during combustion destroyed the soil microbial community, mycorrhizal fungi and soil seed bank in the log burnouts. However, both microbes and seeds of many savanna plants should rapidly disperse into the small, isolated bare patches. Future research should assess how soil nutrient and moisture relations in the burnout patches interact and affect seed germination, mycorrhizal inoculation and microbial activity.

Although information exists about the magnitude and duration of severely burned patches in other regions (Covington et al., 1991; Bauhus et al., 1993; DeBano et al., 1998), we are unaware of reports documenting burnout patterns at other midwestern oak savanna sites. Since the altered soil conditions in these discrete gaps may have a long-term effect on species abundance and distribution patterns in fire-maintained oak savannas, further study should examine the links between changing soil properties and the reinvasion and species dynamics within log burnout patches.

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