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Forest floor fuel dynamics in mixed-oak forests of south-eastern Ohio

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Abstract. Silvicultural treatments alter fuel dynamics in forested systems, which may alter fire regime. Effects of thinning and prescribed fire on forest-floor fuels were studied in mixed-oak forests of south-eastern Ohio to examine fuel dynamics over time. Fuel characteristics were measured before, immediately after, and 3 years following fire and thinning treatments along 20-m transects ($n = 432$) following Brown's planar intersect method. Measurements were taken to determine litter, duff, 1-h, 10-h, 100-h, and 1000-h sound (1000S) or rotten (1000R) fuel mass. Coarse woody debris (CWD) was sampled on 432 additional 80-m^2 belt-transects. Repeated-measures analysis of variance with post-hoc Bonferonni comparisons was used to analyse the change in the fuels over time. The specific effects of silvicultural treatments varied over time with changes in larger, sound fuels (1000S and CWD) persisting longer than changes to finer (litter, duff, 1-h, 10-h, and 100-h) or less-sound (1000R) fuels, which appear to be more transient. Unlike in western North America where fuels accumulate over time, decomposition and productivity appear comparable in eastern mixed-oak forests. Aside from their impact on decomposition or productivity rates, silvicultural treatments appear to have little impact on fine-fuel loading in these systems.

Additional keywords: coarse woody debris; duff; fire ecology; hardwood forests; litter; *Quercus*; silviculture.

Introduction

Fire – naturally occurring as a result of lightning strikes or intentionally set by American Indians – has played a role as an ecological disturbance throughout North America since long before European settlement of the area (Abrams 1992; Pyne *et al*. 1996; Delcourt and Delcourt 1998). In eastern forests, pre-settlement fire regimes are thought to have been driven by aboriginal burning (Day 1953; Buell *et al*. 1954), or possibly by naturally occurring lightning strikes. Fire regimes have been drastically altered in the post-European settlement period, with major shifts occurring between ∼1880 and 1930 following widespread logging, mining, farming, and other intensive land uses (Abrams 1992). These activities often increased fuels (e.g. logging slash) or increased human presence in the area, providing a new source of ignition. As such, they were often followed by stand-replacing fires of a different magnitude than the previous, low-intensity fires common to the region (Brose *et al*. 2001).

The beginning of fire exclusion in the mid-1900s and resulting change in fire regimes may have dramatically altered forest dynamics in the eastern United States. Generally, fire-tolerant species were more common before European settlement than today (Russell 1981; Lorimer 1984; Delcourt and Delcourt 1998; Taylor and Lorimer 2003). Indeed, many authors, including Crow (1988), Abrams (1992, 2003), and Brose *et al*. (2001), maintain that fire was a major driving force behind pre-settlement forest composition. Fire is thought to have increased fire-tolerant species, including oaks (*Quercus* spp.), hickories (*Carya* spp.) and American chestnut (*Castanea dentata*), while simultaneously reducing less fire-tolerant species, chiefly red maple (*Acer rubrum*), sugar maple (*A. saccharum*), and American beech (*Fagus grandifolia*) (Buell *et al*. 1954, 1966; Swan 1970; Crow 1988; Abrams 1992; Schuler and Gillespie 2000).

Fire can have multiple impacts within a forest, and this resulting forest structure and composition can influence future fires. Fire in eastern deciduous forests can strongly alter the herbaceous layer including overstory regeneration (e.g. Hutchinson 2004; Hutchinson *et al*. 2005), but often has less of an immediate impact on overstory canopy trees (Franklin *et al*. 1997). Fire may also have significant impacts on the fuel composition and structure, but the impact of fire on fuel dynamics has rarely been studied in eastern mixed-oak forests (Franklin *et al*. 1997). Inversely, fuel composition, structure, and moisture levels will strongly impact fire behavior. These combined effects can change fire behavior, fire risk, and fire regime, possibly altering the trajectory of fuel dynamics in a region. Furthermore, changes in forest dynamics and fire regimes throughout the 20th century may have reduced the ability of fire to control forest dynamics (Pyne *et al*.

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1996; Franklin *et al*. 2003), which in turn alters the fire regimes.

The specific effects of fire in eastern deciduous forests and the historical role of fire in ecosystem dynamics are still under investigation in many regions, especially in central Appalachia. Regardless, land managers are increasingly using fire or fire-surrogates (i.e. silvicultural thinning) as ecosystem management tools throughout eastern North America. The goal is usually to maintain the current conditions by 'setting back' the progression of ecological succession, or to manage the ecosystem according to a hypothesized prior condition. In eastern mixed-oak forests, this often includes increased oak regeneration and canopy recruitment. Though unintended, these treatments undoubtedly influence fuel loads at the forest floor. Ecosystem treatments such as silvicultural thinning may input debris, whereas prescribed fire consumes fuel. These treatments may also influence the microclimate, and alter the decomposition rates. Unlike western forests where fuel accumulation is an ongoing problem (Brown *et al*. 2004), eastern systems typically exhibit a balance between fuel deposition and decomposition (e.g. Lang and Forman 1978; Onega and Eickmeier 1991). As forest managers continue to implement fire and thinning treatments, it will be increasingly important to know what specific impacts these techniques have on fuel dynamics across the landscape.

We examined fuel dynamics following fire and thinning in south-eastern Ohio to determine how these treatments influence the future fuel composition and structure in eastern mixed-oak forests. Our research was conducted as a component of the Ohio Hills portion of the national Fire and Fire Surrogate (FFS) project (http://www.fs.fed.us/ffs, verified 1 August 2006). The overriding goal of the Ohio Hills FFS research is to determine the effect of three treatments (thinning, prescribed burning, and thinning followed by prescribed burning) on oak regeneration in mixed-oak forests of Appalachian Ohio (Yaussy 2001). In addition to any effects on forest composition, the treatments will impact the fuels. Because fuel dynamics influence future fire regimes (e.g. risk of wildfire, ability to carry a prescribed fire, fire intensity), it is important to determine how the treatments will impact the fuels over time.

As productivity and decomposition act very strongly on fuels in the east, we hypothesized that fuel loads would recover quickly following fire and fire-surrogates except when the treatments substantially changed the microclimate. We used multiple fuel classes, from leaf litter to coarse woody debris, to examine the fuel dynamics over 3 years following treatment. Our aim was to determine the temporal dynamics of fuels in eastern mixed-oak forests following fire and fire-surrogates. Our goals were: (1) to measure the fuel loading 3 years following the treatments; and (2) to analyze changes to the fuel loading between treatments and over time.

Methods

Site description

Three study sites were located throughout south-eastern Ohio: Tar Hollow State Forest (39°33′0″N 82°76′7″W) in Ross County; the Raccoon Ecological Management Area (REMA, part of the Vinton Furnace Experimental Forest; 39°20′0″N 82°39′0″W) in Vinton County, and Zaleski State Forest (39°35′5″N 82°37′0″W) in Vinton County (Yaussy 2001). The three sites are part of the Low Hills Belt of the Unglaciated Allegheny Plateau (Braun 1950). All three feature deeply dissected topography (75–100-m relief) over sedimentary bedrock (Forsyth 1970). The climate is damp year-round, with an average annual precipitation of 1006 mm spread evenly throughout the year (NOAA 2006). Winters tend to be mild, with an average temperature of −2°C in January; summers tend to be relatively warm, with an average temperature of 22.6°C in July (NOAA 2006). Moisture gradients are strong as a result of the topographic relief; north- and east-facing slopes tend to be mesic, whereas south- or west-facing slopes are drier (Wolfe *et al*. 1949; Iverson *et al*. 1997). Braun (1950) classified this region as mixed-mesophytic forest, with a higher presence of oak and hickory than in other regions of this type. Following regeneration from extensive clearing throughout the 19th and 20th centuries, the communities currently found at the study sites resemble the oak–hickory association (Braun 1950) as well as mixed-mesophytic forest.

Each site included three ∼25-ha treatment units (thinning, burning, and thinning followed by burning) and a control unit. Thinning from below to basal area ∼13.75 $m^2 ha^{-1}$ (an ∼30% reduction in basal area) was performed during the fall and winter of 2000 (Yaussy 2001; Iverson *et al*. 2004). This level of thinning represents the upper bound of what is typical for selective thinning in eastern deciduous forests. Prescribed fires were conducted over an 8-day period during late March and early April 2001 (Iverson *et al*. 2004). All of the burns were conducted under fairly cool, damp conditions with low wind speeds Iverson *et al*. (2004).

Field methods

The planar-intercept method (Brown 1974) was used to sample fuels along two 20-m transects (vertical planes) at each of 36 grid points per unit ($n = 36$ per unit, total $n = 432$; Fig. 1). Coarse woody debris (CWD; woody debris on ground, large end >15.0 cm, small end >7.6 cm) was also sampled along 36 additional 80-m^2 belt-transects per unit ($n = 36$ belt-transects per unit, total $n = 432$; Fig. 1). Litter and duff depth measurements were taken at three spots on each fuel transect (at 5.0, 10.0, and 15.0 m). Litter was defined as freshly fallen litter or other organic material still taxonomically and morphologically identifiable. Duff was defined as unidentifiable organic matter above the mineral soil and below the litter. Vertical fuel height measurements were taken at three

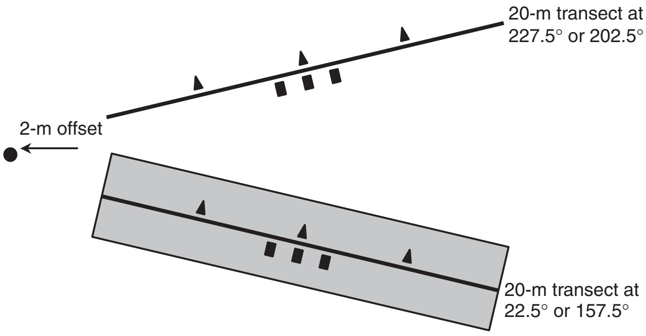

Fig. 1. Planar intersect method of sampling fuels and coarse woody debris. ● represents the grid point ($n = 36$ per unit, total $n = 432$), ▲ represents litter and duff depth measurements (at 5, 10, 15 m), ■ represents vertical height measurements (at 8, 10, 12 m), thick lines represent two 20-m transects, shaded box represents 80 m^2 coarse woody debris belt-transect. The 1-h and 10-h fuels are tallied between 8 and 12 m on each transect. The 100-h fuels are tallied between 9 and 11 m on each transect. The 1000-h fuel species, diameter and decay status (sound or rotten) are tallied along the entire 20 m of each transect. Coarse woody debris species, large diameter (diameter >15 cm), small diameter, length, decay class (decay class I–V [Brown 1974]) and rating (more or less than 50% of log located in transect) are measured within the belt-transect. Figure adapted from Yaussy (2001).

30 cm-long locations on each transect (beginning at 8.0, 10.0, and 12.0 m). All downed, dead fuel immediately above the 30-cm section of transect was included in the vertical height measurement; living plants (e.g. shrubs, trees) and dead wood connected to living plants were not included in the vertical height. Count tallies for 1-h fuels (0–6-mm diameter where they cross the transect) and 10-h fuels (6–25-mm diameter) were taken between 8.0 and 12.0 m on each transect. Also, 100-h fuels (25–75-mm diameter) were tallied between 9.0 and 11.0 m on each transect. Species, diameter, and decay status for 1000-h fuels (sound – 1000S, or rotten – 1000R; diameter >75 mm) were tallied along the entire 20 m of each transect. When 1000-h or CWD species were not readily identifiable in the field, a slice of wood was removed and identified in the laboratory (Hoadley 1990). Tilt angle (a), piece diameter (d^2), and specific gravity (s) corrections to the Brown transect formulas were necessary to account for the high diversity of eastern forests, and were provided in Riccardi (2005). Formulas used to convert litter and duff depths to dry mass were taken from Riccardi (2005). Coarse woody debris species, large diameter (diameter >15.0 cm), small diameter (diameter >7.6 cm), length (length >1.0 m), decay class I–V (McCarthy and Bailey 1994), and rating (more or less than 50% of log length located in belt-transect) were measured on the 80-m^2 belt-transect. Specific gravity values for each species were taken from Hoadley (1990) and from Adams and Owens (2001) and used to calculate 1000-h and CWD mass.

Data analysis

Data were normalized via a log-transformation. A mean value for each treatment unit was calculated for each year (three sites with four treatments and 3 years, $n = 36$), and randomized complete block design, two-way factorial analysis of variance with post-hoc Bonferroni comparisons was performed using PROC MIXED in SAS (Littell *et al.* 1996; SAS Institute 2001). Site was classified as a random effect, treatment unit was classified as a fixed effect, and year of measurement was used as the repeated measure. The specific model statement used was (example is for litter): class site fire thin year; model litter = site fire|thin year fire|thin|year/noint solution; random site; repeated year.

Pretreatment data (2000) and first year post-treatment data (2001) were collected as a part of an Ohio University PhD dissertation (Riccardi 2005) and archived for public access at the USDA Forest Service Northeastern Research Station (Delaware, OH, USA). We collected a second round of data using identical methods during June–August 2004 to analyze changes in fuel composition over the 3-year period following the first round of treatments. Unless otherwise noted, all fuel-mass values are reported in Mg ha^{-1}, CWD density values are reported in logs ha^{-1}, CWD volume values were calculated using Smalian's formula for log volume (Avery and Burkhart 1994) and are reported in m^3 ha^{-1}, and error calculations represent the standard error of the mean.

Results and discussion

The specific effects of fire and fire-surrogates vary among treatments, among fuel types, and over time (Table 1). Changes to the larger, sound fuels (1000S and CWD density) persist over time, whereas changes in finer fuels (litter, duff, 1-h, 10-h, and 100-h) or less-sound coarse fuels (1000R) are more transient, recovering within 3 years after fire and thinning. These effects are related to the specific characteristics of each treatment and fuel type. In general, year and at least 1 year × treatment interaction were significant for all fuel classes except litter, which was only influenced by year (Table 2). The thin × year interaction was significant for duff, 10-h, 100-h, 1000S, 1000R, and CWD (mass, density, and volume). The fire × year interaction was significant for litter, 1000R, and CWD (mass, density, and volume).

By 2004, fine fuel levels had converged in all treatments. Litter loading was somewhat greater in thin units (Fig. 2*a*) and duff loading less in combined treatments (Fig. 2*b*), but neither of these differences was statistically significant (all $P > 0.05$). Smaller woody fuels had likewise converged by 2004; 1-h and 10-h fuels were the same within all treatments (Fig. 3*a*, *b*), whereas 100-h fuels appeared somewhat greater in thinning treatments, but not significantly so after Bonferroni correction ($P = 0.20$; Fig. 3*c*).

Our values for fine fuels are largely consistent with prior published values in hardwood forest. In a review of forest floor carbon mass, Smith and Heath (2002) reported dry-weight litter masses ranging from 4.6 to 92.2 Mg ha^{-1} (mean of 28.0 ± 5.1 Mg ha^{-1}) for 26 studies in oak or mixed-oak

Table 1. Effects of fire and fire surrogate treatments in 2001 and 2004
All increases and decreases mentioned are statistically significant with respect to the control at the $P = 0.05$ level. 1000R, 1000-h rotten fuel mass; 1000S, 1000-h sound fuel mass; CWD, coarse woody debris

Treatment	1 year post treatment (2001)	3 years post treatment (2004)
Thinning	Increased 1-h, 10-h, 100-h, 1000S, CWD, and litter; decreased 1000R fuels	Increased 1000S and CWD density
Burning	Increased duff; decreased 1000R and litter	All recovered
Thinning and burning	Increased 1-h, 10-h, 100-h, 1000S, CWD, and duff; decreased 1000R and litter	Increased 1000S and CWD density

forests in the northern portions of the United States. Kucera (1952) reported litter mass values from 2.35 to 5.38 Mg ha^{-1} and duff values from 8.40 to 14.90 Mg ha^{-1} in a hardwood forest in central Iowa. Metz (1954) reported forest floor litter weight of 5.86 ± 3.30 Mg ha^{-1} in the Piedmont of South Carolina. Crosby and Loomis (1974) reported litter values of 3.63 to 7.53 Mg ha^{-1} in black oak stands of southeastern Missouri. Similarly, Gathany (2004) reported litter dry weights from 3.8 to 14.1 Mg ha^{-1} in Dysart Woods, Belmont County, Ohio. Our dry-weight litter values (Table 3) were within these ranges (Kucera 1952; Metz 1954; Crosby and Loomis 1974; Gathany 2004), but on the lower end of those reported by Smith and Heath (2002). The differences between these results are probably related to topography; our study was conducted in the topographically diverse Ohio Hills region, whereas many of the studies reported by Smith and Heath (2002) were conducted on more level terrain. Onega and Eickmeier (1991) reported total fine woody debris mass (up to 3 cm in diameter, roughly equivalent to our 1-h and 10-h fuels together) of 5.1 Mg ha^{-1}. The combined values for our 1-h and 10-h fuel masses are similar to these values (from 6.2 to 7.8 Mg ha^{-1}; Table 3).

Larger woody fuels exhibited a distinctly different pattern from fine fuels in 2004. As a result of silvicultural thinning, sound fuels (100-h, 1000S, and CWD) were greater in the thin and thin followed by burn treatments than in the control (Figs 3*c*, *d* and 4). Rotten fuels behaved differently from sound fuels: no differences were reported in the 1000R fuels for any of the treatments (Fig. 5).

Our values for large woody fuels are similar to prior studies. McCarthy and Bailey (1994) reported CWD density values of around 400 logs ha^{-1}, mass values of 18–35 Mg ha^{-1}, and volume values of 40–60 m^3 ha^{-1}, in standing, managed deciduous forests in Maryland. Onega and Eickmeier (1991) reported a CWD (>3 cm diameter) mass value of 14.2 Mg ha^{-1} in southern Tennessee. McCarthy *et al.* (2001) reported CWD density of 637.1 logs ha^{-1} and volume of 335.0 m^3 ha^{-1} in an old-growth forest (Dysart Woods) in Belmont County, Ohio. Harmon *et al.* (1986) reported CWD volume values of 94–132 m^3 ha^{-1}, and mass values of 21–24 Mg ha^{-1} for second-growth mixed-oak and *Quercus prinus* stands in Tennessee. Our values for larger woody debris were consistent with these reported ranges (Table 3).

Our results verify the need to measure and analyze 1000-h sound and rotten fuels separately. Aside from having disparate ecological impacts, 1000-h fuels differ in response to treatments depending on whether they are sound (1000S) or rotten (1000R). Unlike 1000S fuels, which increase immediately following thinning treatments (i.e. thinning, and thinning followed by burning), the softer, partially decomposed 1000R fuels decrease after these same treatments, possibly owing to changes in decomposition rates. Moreover, physical maceration by logging equipment was likely a factor in the reduction of 1000R following thinning. This decrease in 1000R fuels had mostly recovered by 2004. Interestingly, 1000S were somewhat greater in the burning treatment than in the control in 2004, but 1000R had all recovered by 2004.

Thinning treatments initially input a large quantity of woody fuels to the forest floor. This effect is seen in 2001 in nearly all woody-fuel classes: 1-h, 10-h, 100-h, 1000S, and CWD. This result was to be expected, because treetops, non-merchantable timber and other woody debris are felled, trimmed and abandoned during the thinning process. But, the legacy from thinning is only still significant in 2004 for the larger, sound fuel classes (1000S and CWD) and is present (though not statistically so) in 100-h fuels. All fine fuels quickly equilibrate to a constant level likely dictated by local decomposition rates.

Thinning had a different impact on fine fuels and small woody fuels than on larger woody fuels. When thinning removes canopy cover, ecosystem processes, including air flow, light, and rain penetration, all increase at the forest floor (Zheng *et al.* 2000). Subsequently, decomposition accelerates, and smaller fuels are likely to be removed from the system at a greater rate. Thinning had little initial impact on litter but increased duff compared with the control. Although it was not mirrored by a decrease in litter, this increase in duff was most likely caused by increased decomposition of the leaf litter during the spring of 2001. By 2004, litter appeared to have increased; although this increase is not statistically significant, it is probably ecologically significant and likely due to an increase in herbaceous plants and shrubs under the forest canopy in these units (T. Hutchinson, USDA Forest

Table 2. Maximum likelihood analysis of variance table for fixed effects and repeated-measures for fuels

1-h (0–6 mm diameter), 10-h (6–25 mm), 100-h (25–75 mm) and 1000-h (75+ mm) sound (1000S) or rotten (1000R), litter, duff and coarse woody debris (CWD) mass, density and volume were analysed in 2004 using 2001 and 2000 data as the repeated-measure (year). Numerator and denominator degrees of freedom ('Num d.f.' and 'Den d.f.' respectively) were provided by SAS PROC MIXED (Littell *et al.* 1996; SAS Institute 2001)

Effect	1-h fuels				10-h fuels				100-h fuels				1000S fuels				1000R fuels			
	Num d.f.	Den d.f.	*F*-value	*P*-value	Num d.f.	Den d.f.	*F*-value	*P*-value	Num d.f.	Den d.f.	*F*-value	*P*-value	Num d.f.	Den d.f.	*F*-value	*P*-value	Num d.f.	Den d.f.	*F*-value	*P*-value
Fire	1	22	0.04	0.8491	1	22	0.38	0.5462	1	22	0.60	0.4474	1	22	1.33	0.2606	1	22	2.62	0.1199
Thin	1	22	0.18	0.6726	1	22	3.76	0.0654	1	22	30.10	<0.0001	1	22	22.81	<0.0001	1	22	0.25	0.6193
Fire × Thin	1	22	0.07	0.7994	1	22	0.44	0.5137	1	22	0.00	0.9927	1	22	1.36	0.2567	1	22	0.01	0.9063
Year	2	22	14.46	<0.0001	2	22	26.07	<0.0001	2	22	212.61	<0.0001	2	22	26.24	<0.0001	2	22	25.87	<0.0001
Fire × Year	2	22	0.27	0.7683	2	22	1.31	0.2894	2	22	0.05	0.9560	2	22	0.35	0.7109	2	22	3.70	0.0413
Thin × Year	2	22	2.49	0.1059	2	22	14.27	0.0001	2	22	13.81	0.0001	2	22	13.87	0.0001	2	22	8.39	0.0020
Fire × Thin × Year	2	22	0.19	0.8294	2	22	2.10	0.1463	2	22	0.48	0.6227	2	22	1.31	0.2911	2	22	2.30	0.1241

Effect	Litter				Duff				CWD mass				CWD density				CWD volume			
	Num d.f.	Den d.f.	*F*-value	*P*-value	Num d.f.	Den d.f.	*F*-value	*P*-value	Num d.f.	Den d.f.	*F*-value	*P*-value	Num d.f.	Den d.f.	*F*-value	*P*-value	Num d.f.	Den d.f.	*F*-value	*P*-value
Fire	1	22	12.41	0.0019	1	22	0.14	0.7073	1	22	4.48	0.0458	1	22	6.90	0.0154	1	22	5.73	0.0256
Thin	1	22	1.30	0.2669	1	22	4.56	0.0441	1	22	13.25	0.0014	1	22	22.82	<0.0001	1	22	10.87	0.0033
Fire × Thin	1	22	0.79	0.3830	1	22	0.29	0.5970	1	22	6.33	0.0196	1	22	9.11	0.0063	1	22	6.48	0.0184
Year	2	22	14.42	<0.0001	2	22	67.16	<0.0001	2	22	1.82	0.1863	2	22	4.01	0.0328	2	22	2.39	0.1148
Fire × Year	2	22	10.75	0.0006	2	22	0.77	0.4747	2	22	0.00	0.9956	2	22	0.10	0.9038	2	22	0.03	0.9671
Thin × Year	2	22	0.71	0.5032	2	22	6.36	0.0066	2	22	5.29	0.0133	2	22	9.43	0.0011	2	22	4.46	0.0236
Fire × Thin × Year	2	22	0.10	0.9032	2	22	2.00	0.1589	2	22	0.13	0.8817	2	22	0.32	0.7271	2	22	0.12	0.8850

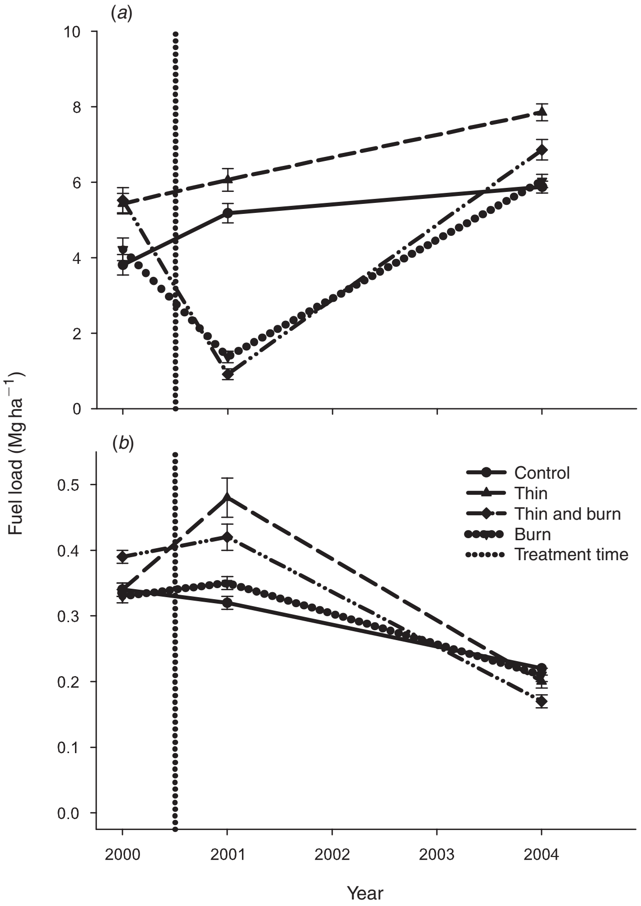

Fig. 2. Mean fuel load values for (*a*) litter and (*b*) duff. Pre-treatment values are given for 2000, post-treatment values are given for 2001 and 2004. Error bars represent the standard error of the mean. Statistically significant differences are represented by different letters within each graph. Note different scales on the *y*-axes.

Service, personal communication). At the same time, 1-h fuels were less in thinned units than in the control; once again, this difference is likely to be ecologically important despite its statistical insignificance. Similarly to the litter in 2001, the observed decrease in 1-h fuels in 2004 was most likely due to an increase in decomposition related to the opening of the canopy from thinning in 2000–2001.

Burning treatments had little initial impact on the majority of fuels in 2001. The only fuel class that fire greatly impacted in 2001 was litter. The dramatic reduction in litter in burned units meets expectations, as litter is the main carrier of fire in mixed-oak forests of southern Ohio. Additionally, a slight increase in duff mass was apparent. This increase in duff was probably the effect of incomplete litter combustion subsequently forming duff. The reduction in litter and minimal impacts on duff correlate well with similar studies of fire in the southern Appalachians (e.g. Elliott and Vose 2005). Few impacts of fire were seen in the woody fuels. A slight increase in 1000R was the only impact to woody fuel mass. This impact was not statistically significant, but was probably related to flames charring some 1000S logs; over 3 years, these logs experienced rapid decomposition, and were subsequently measured as rotten in 2004.

By 2004, smaller fuels (litter, duff, 1-h, 10-h, and 100-h) had all recovered in burned units, whereas a slight increase in 1000S and a slight decrease in 1000R became apparent. The change in 1000S was less severe than in thinned units, and was not seen in the CWD. Personal observations suggest that the increase in 1000S was related to fire-damaged trees beginning to die and fall. It may also have been related to an observed regional increase in white oak mortality over the past few years (R. Long, USDA Forest Service, personal communication). As these and other trees senesce, the short-term impact will begin to mirror that from thinning (e.g. an increase in decomposition, changes to the ground vegetation, impacts on CWD and 1000-h fuels). The decrease in 1000R is probably related to two factors: consumption of wood by fire, and increased rates of decomposition from the recently opened canopy as standing trees die and fall.

The combination of thinning and burning only had one effect in 2004 that was not seen in either treatment alone. Duff was less in the thin followed by burn treatment than in the other treatments. This was likely the result of a combined effect between the two treatments: burning removed much of the litter in 2001 (and thus removed some of the influx to the duff layer), whereas thinning-related increases in decomposition reduced the duff itself over 3 years. In the combined treatment, woody fuels that were added through thinning were not allowed to dry out over a complete growing season. Had the woody fuels been given sufficient drying time between treatments (e.g. an entire growing season), an interactive effect between thinning and fire may have been observed.

The effects of fire and thinning on fuel loads in eastern mixed-oak forests are quite different from their effects in western forests. In the western USA, fuel build-up over time is a strong driver behind fuel dynamics (Agee and Huff 1987). Much of the western fuel build-up is related to conditions being less favorable for decomposition in the soil moisture, microclimate, and nutrient content of the litter (Valachovic *et al*. 2004). Furthermore, drier conditions and slower turnover of pine litter in western forests (Quideau *et al*. 2001) reduce the decomposition rates when compared with eastern forests. Low decomposition rates then cause fuels to accumulate over time. Long-term fuel build up is a major issue (e.g. Brown *et al*. 2004) driving fire risk, fire regime, and restoration strategies for western ecosystems. Fine fuels in particular accumulate at much greater rates than in eastern forests. For example, Stephens and Moghaddas (2005) found litter fuel loads to range from 45 to 138 Mg ha^{-1}, an order of magnitude above both what we found in Ohio and those reported for other eastern mixed-oak

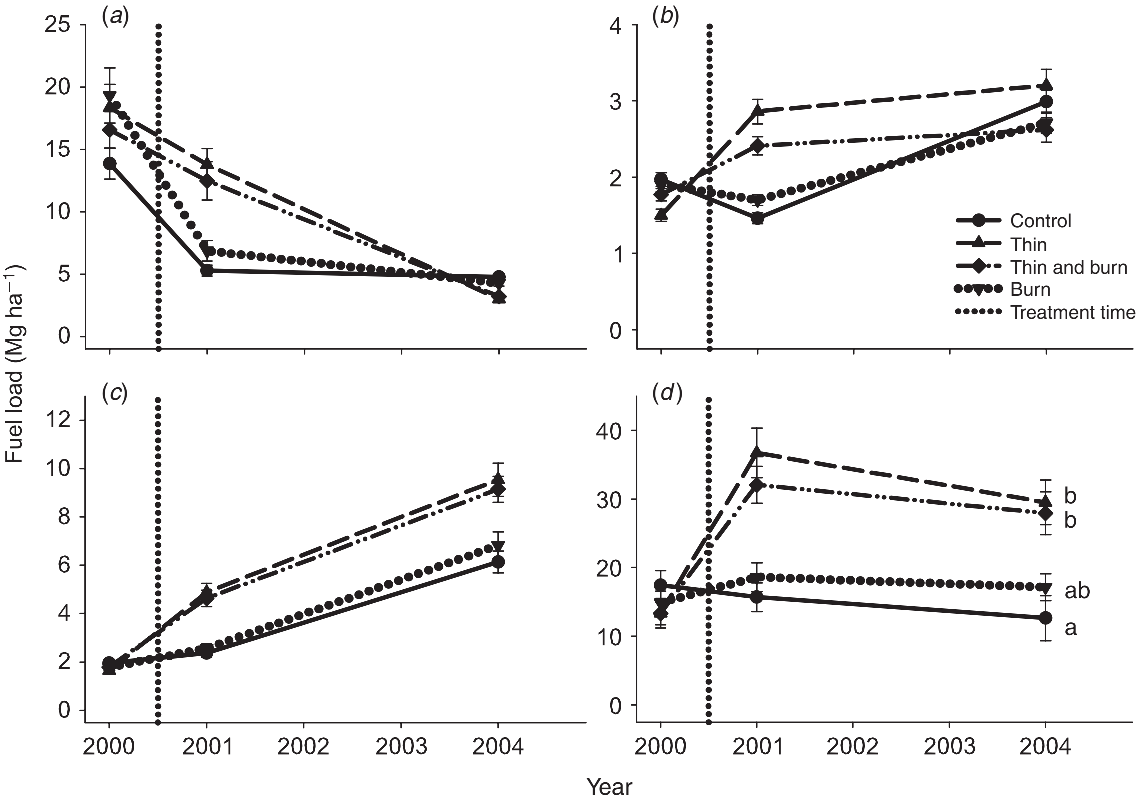

Fig. 3. Mean fuel load values for (*a*) 1-h fuels, (*b*) 10-h fuels, (*c*) 100-h fuels, and (*d*) 1000-h sound fuels. Pre-treatment values are given for the 2000 data, post-treatment values are given for 2001 and 2004. Error bars represent the standard error of the mean. Statistically significant differences are represented by different letters within each graph. Note different scales on the *y*-axes.

forests (e.g. Lang and Forman 1978; Smith and Heath 2002; Gathany 2004).

In marked contrast, increased decomposition rates in eastern forests quickly remove most of the fine fuel mass (Lang and Forman 1978; Onega and Eickmeier 1991; Riccardi 2005). Onega and Eickmeier (1991) reported western Douglas-fir woody detritus half-lives at 23.1 years in contrast to eastern deciduous forests where they reported woody debris half-lives ranging from only 2.7 to 3.8 years. Lang (1974) and Lang and Forman (1978) reported turnover rates for fine fuels (litter, small woody fuel, and fruits) in eastern mixed-oak forests ranging from 1 to 5 years, with most locations falling into the range 1.6–2.7 years. Our results verify the assertion that long-term fuel accumulation does not occur in eastern mixed-oak forests. Topographic variation, fuel moisture, and spatial variability will all play a strong, site-specific role in determining fire behavior, fire regime, and fire risk. Fuel dynamics over time appear to be less cyclical than in western forests. Because eastern fuel dynamics occur on shorter timescales than those in the west (i.e. years to decades instead of decades to centuries), fire and fire surrogate treatments will have a limited impact on the fuels over extended periods of time. The specific balance between productivity and decomposition will be the most important driving force behind eastern hardwood fuel dynamics. Finer-scale variables including microclimate, topography, and local impacts from silvicultural treatments will have more influence on fuel dynamics than will stand-level treatments.

Conclusions

The effects of fire and thinning vary over time in eastern mixed-oak forests. Impacts on large, sound fuels persist longer than impacts on fine or rotten fuels. Unlike in western forests where fuel loading is a major driving force behind fire ecology, fire regimes in eastern forests are less likely to be directly influenced by long-term fuel build up. Fuel dynamics will be driven by the relative balance between productivity and decomposition. Stand-level treatments will have little lasting impact on fuel loading. As eastern fires are primarily influenced by litter and 1-h fuels, the dynamics of these fuel classes will have the greatest impact on fire regimes. In general, litter and 1-h fuels converge rapidly following stand-level silvicultural treatments. Although the

Table 3. Means of fuel estimates by treatment unit in 2000, 2001, and 2004 (± s.e.m.)

Mass values are given in Mg ha^{-1}, coarse woody debris (CWD) density values are given in logs ha^{-1}, CWD volume values are given in m^3 ha^{-1}. Means were calculated based on the subsamples ($n = 36$ per treatment unit, total $n = 864$). 1000R, 1000-h rotten fuel mass; 1000S, 1000-h sound fuel mass

Fuel	Control			Thin			Thin and burn			Burn		
	2000	2001	2004	2000	2001	2004	2000	2001	2004	2000	2001	2004
1-h	13.85 ± 1.24	5.29 ± 0.44	4.77 ± 0.19	18.40 ± 1.88	13.79 ± 1.27	2.99 ± 0.20	16.57 ± 1.47	12.47 ± 1.54	3.21 ± 0.20	19.33 ± 2.21	6.86 ± 0.83	4.27 ± 0.23
10-h	1.97 ± 0.09	1.46 ± 0.07	2.99 ± 0.17	1.50 ± 0.08	2.86 ± 0.16	3.20 ± 0.21	1.77 ± 0.08	2.41 ± 0.12	2.62 ± 0.18	1.90 ± 0.09	1.70 ± 0.07	2.71 ± 0.15
100-h	1.95 ± 0.16	2.36 ± 0.17	6.14 ± 0.43	1.64 ± 0.15	4.88 ± 0.36	9.54 ± 0.78	1.79 ± 0.14	4.63 ± 0.34	9.14 ± 0.56	1.78 ± 0.12	2.56 ± 0.18	6.82 ± 0.66
1000S	17.42 ± 2.17	15.70 ± 2.10	12.66 ± 2.30	13.39 ± 2.16	36.70 ± 3.59	29.50 ± 3.27	13.30 ± 1.65	32.07 ± 2.68	27.93 ± 3.12	14.89 ± 1.69	18.61 ± 2.09	17.17 ± 1.96
1000R	2.71 ± 0.68	5.50 ± 0.78	5.69 ± 1.00	5.24 ± 0.76	3.36 ± 0.57	4.80 ± 0.61	9.60 ± 1.76	3.72 ± 0.73	6.28 ± 0.98	5.48 ± 0.76	5.87 ± 1.00	4.92 ± 0.83
Litter	3.82 ± 0.27	5.18 ± 0.26	5.87 ± 0.20	5.43 ± 0.27	6.06 ± 0.30	7.85 ± 0.25	5.52 ± 0.33	0.91 ± 0.14	6.86 ± 0.34	4.22 ± 0.30	1.37 ± 0.150	6.03 ± 0.21
Duff	0.34 ± 0.01	0.32 ± 0.01	0.22 ± 0.01	0.34 ± 0.01	0.48 ± 0.03	0.20 ± 0.01	0.39 ± 0.01	0.42 ± 0.02	0.17 ± 0.01	0.33 ± 0.01	0.35 ± 0.01	0.21 ± 0.01
CWD mass	16.61 ± 2.56	12.72 ± 1.78	26.22 ± 5.39	20.23 ± 4.99	23.66 ± 2.35	46.07 ± 8.78	18.53 ± 3.29	24.80 ± 2.72	37.58 ± 6.05	26.67 ± 5.23	17.95 ± 2.20	30.82 ± 5.48
CWD density	192.13 ± 19.69	167.82 ± 18.91	134.26 ± 14.77	199.07 ± 19.11	399.31 ± 31.74	304.40 ± 27.97	190.97 ± 19.21	430.56 ± 35.78	297.45 ± 25.51	280.09 ± 24.55	262.73 ± 26.92	180.56 ± 17.12
CWD volume	35.23 ± 5.38	25.97 ± 3.84	64.69 ± 12.09	41.62 ± 9.97	42.92 ± 4.27	98.28 ± 17.92	37.36 ± 5.62	46.03 ± 4.84	88.43 ± 13.43	54.53 ± 9.08	38.36 ± 4.61	74.80 ± 10.77

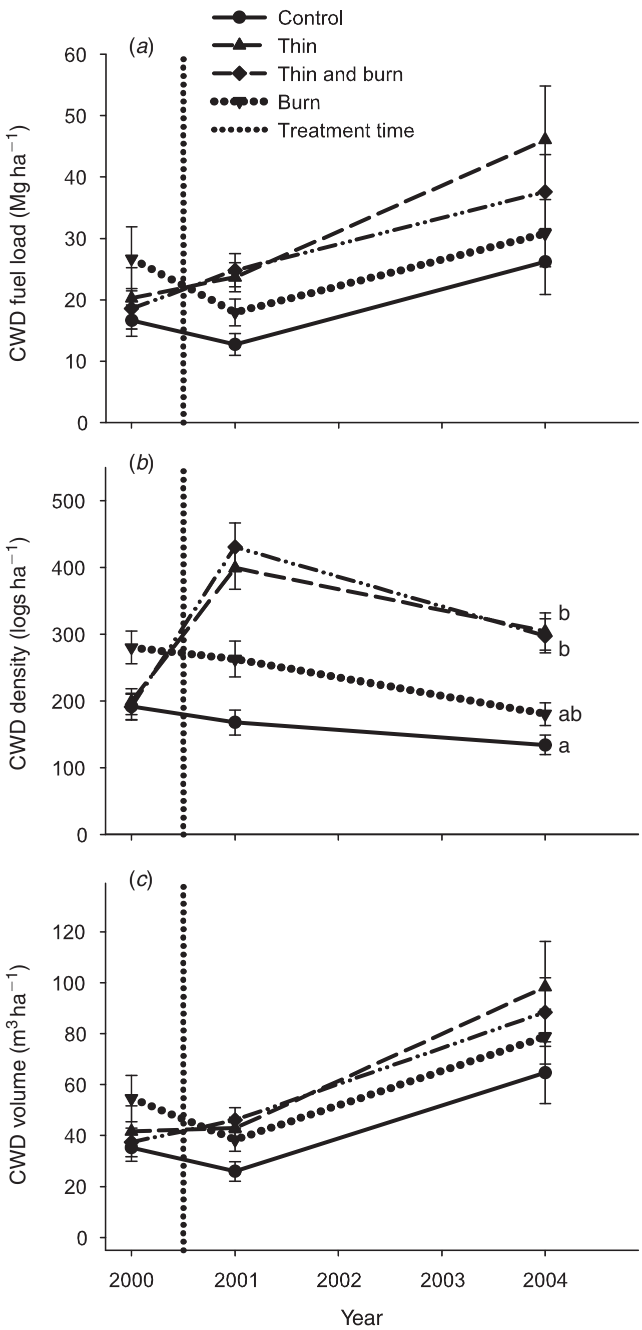

Fig. 4. Mean values for coarse woody debris (CWD) (*a*) mass, (*b*) density, and (*c*) volume. Pre-treatment values are given for the 2000 data, post-treatment values are given for 2001 and 2004. Error bars represent the standard error of the mean. Statistically significant differences are represented by different letters within each graph. Note different *y*-axes.

effects of fire and thinning on larger fuels are less likely to influence future fire ecology, they may have effects on other ecological processes and functions including animal diversity, seedling establishment, soil characteristics, and carbon sequestration.

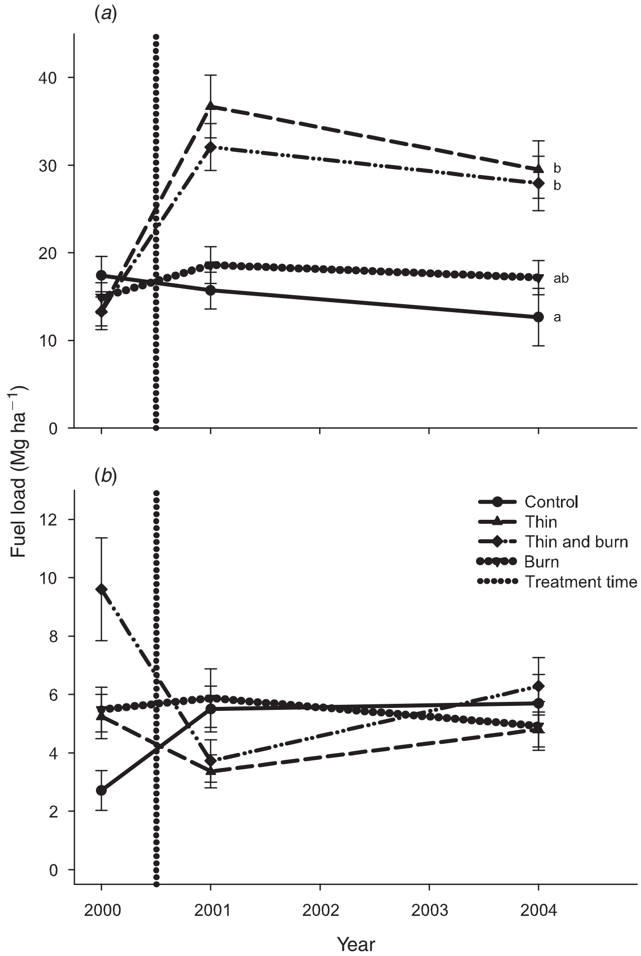

Fig. 5. Mean fuel load values for (*a*) 1000-h sound, and (*b*) 1000-h rotten fuels. Pre-treatment values are given for the 2000 data, post-treatment values are given for 2001 and 2004. Error bars represent the standard error of the mean. Statistically significant differences are represented by different letters within each graph. Note different scales on the *y*-axes.

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