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Fire Behavior and Fire Effects on Eastern Redcedar in Hardwood Leaf-Litter Fires

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Abstract. Treatment of stands of hardwoods in the cross timbers of the central United States with tebuthiuron (N-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-N,N'-dimethylurea) can significantly decrease canopy cover of hardwoods. However, at the rate used for hardwood control, tebuthiuron does not control eastern redcedar (*Juniperus virginiana* L.). Our objective was to determine the potential of using fires in the hardwood leaf litter, either before or after tebuthiuron, for controlling eastern redcedar. To do this, we compared fuelbed characteristics, fire behavior, and fire effects on eastern redcedar in naturally occurring hardwood leaf litter with those augmented by leaves dropped following a single application of tebuthiuron. Studies were conducted in 1988, 1989, and 1991 on a cross timbers site dominated by an overstory of post oak (*Quercus stellata* Wangenh.) and blackjack oak (*Q. marilandica* Muenchh.) and with eastern redcedar in the understory. Factors evaluated included herbicide treatment (tebuthiuron or no herbicide) and burning season (late summer or winter). Tebuthiuron at 2.2 kg a.i. ha^{-1} was applied to plots (25 X 25 m) in March of the study years. In late summer, tebuthiuron-treated plots contained almost twice the 1-hr fuel loading as untreated plots. Fuel depth on untreated plots in late summer was about half that of other herbicide treatments and burning date combinations. Fuel loading on plots burned in winter was not affected by tebuthiuron treatment, and no differences in fuel consumption were detected among any treatments. Moisture content of 1-hr fuels on plots burned in winter was more than twice that of 1-hr fuels on plots burned in late summer. Fire intensity was low with all burns, and no differences in fire behavior were detected among any treatments. Crown scorch of 75% or greater on small eastern redcedar trees was considered a successful burn, and this resulted on all but the late summer-no tebuthiuron treatment. The natural log of fireline intensity explained about 47% ($P<0.0006$) of the variation in fire success, and ambient air temperature explained an additional 19% ($P<0.0468$). Although tebuthiuron treatments effectively augmented leaf-litter fuel load by late-summer and provided a suitable fuelbed for burning, crown scorch and tree kill were not greatly improved by burning in late summer as compared to winter. We conclude that understory eastern redcedar can be controlled successfully by burning leaf-litter fuelbeds in either late fall or winter after natural leaf-fall from hardwood trees or in late summer, fall, or winter following a spring application of tebuthiuron for control of overstory hardwoods.

Keywords: Crown scorch; Prescribed burning; *Juniperus virginiana*; Herbicides; Tebuthiuron; Oklahoma.

Introduction

The cross timbers, the western edge of the temperate deciduous forest in North America (Barnes 1991), form a substantial potential forage base for livestock producers in Oklahoma, northeastern Texas, and southeastern Kansas, USA. Like closed forests throughout the world, most of the cross timbers do not produce commercially valuable timber or contribute significant forage for livestock and wildlife because of dense tree overstory. Burning for control of woody plants in closed forests is usually not a viable option because the woody overstory prevents sufficient grass fuel to support intense fires (Trollope 1984). However, treatment of these areas with herbicides significantly decreases overstory canopy cover and increases herbaceous diversity (Engle et al. 1991). This increases forage production, livestock carrying capacity, and populations of game animals (Lochmiller and Engle 1992, McCollum et al. 1992). Similar increases in forage production with overstory reduction by herbicides occur in forests and shrublands throughout the world (e.g., Crowder and Chheda 1982, Scifres 1980).

Woody species respond differently and often show resistance to some herbicides (Crowder and Chheda 1982, Scifres 1980). Thus, follow-up herbicide treatments or combinations of other control measures such as burning and mechanical control are often needed to maintain the initial treatment benefits. In the cross timbers, tebuthiuron (N-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-N,N'-dimethylurea) is an effective herbicide for control of hardwoods, but it is not effective on eastern redcedar (*Juniperus virginiana* L.) (Stritzke 1978, Stritzke et al. 1991). As a result, eastern redcedar rapidly becomes the dominant woody species and will eventually nullify the benefits of the initial tebuthiuron treatment.

Because eastern redcedar do not resprout, trees to 1.5 m in height can be effectively and economically killed by moderately intense spring fires in grasslands (Bernardo et al. 1988, Engle et al. 1988). In the understory of mature hardwood communities treated with tebuthiuron, however, eastern redcedar are not adequately controlled with follow-up spring burning because fine fuel from warm-season grasses is insufficient to support fires of an intensity necessary to kill redcedar (Stritzke et al. 1991). Much of the hardwood leaf litter is mineralized by the first spring after tebuthiuron application and the fine fuels produced by early successional understory herbaceous species (cool-season grasses and warm-season forbs) in subsequent years will not support continuous ignition (Engle et al. 1991, Stritzke et al. 1991). Eastern redcedar released from overstory competition quickly grow beyond the size at which they can be controlled effectively by fire. Thus, eastern redcedar presents a major problem to managers of these lands (Snook 1985).

Leaf-litter fires have been effectively used in the fall for seedbed preparation for overseeding grasses in both untreated and recently herbicide-treated stands. Leaf-litter fires have also been used for precommercial thinning of pines after hardwood control (Crawford and Bjugstad 1967, Stritzke et al. 1975, Nickles et al. 1981). These studies suggest that additional leaf litter resulting from herbicide-induced defoliation could result in fires of greater intensity for controlling herbicide-resistant woody species such as eastern redcedar.

Our overall objective was to determine the potential of using fires in hardwood leaf litter either before or after tebuthiuron to control eastern redcedar. To accomplish this objective we compared fuelbed characteristics and fire behavior between sites with naturally occurring hardwood leaf litter and those augmented by leaves dropped following a single application of tebuthiuron for hardwood control. We also compared the effects of late-summer and winter leaf-litter fires on crown scorch and tree kill of understory eastern redcedar in both naturally occurring hardwood leaf litter and leaf litter that had been augmented by leaves following application of tebuthiuron.

Methods and Materials

Experimental Area and Experimental Design

The studies were conducted in northcentral Oklahoma on the Oklahoma State University Research Range, located approximately 15 km southwest of Stillwater. The area is in the western extension of the oak-hickory forest in what is commonly referred to as the cross timbers. The vegetation on the site is dominated by an overstory of post oak (*Quercus stellata* Wangenh.) and blackjack oak (*Q. marilandica* Muenchh.).

Studies were conducted in 1988, 1989, and 1991. Factors evaluated included herbicide treatment (tebuthiuron or no herbicide) and burning season (late summer or winter). Tebuthiuron at 2.2 kg a.i. ha^{-1} was applied to plots (25 X 25 m) in March of the study years. Burns were conducted the first respective burning date post-herbicide application. Burns were applied as strip headfires to plots, which were established on level topography. The late-summer burns were conducted the year of tebuthiuron application and prescribed for warm, dry weather (i.e., approximately 40% relative humidity and 20 to 30° C ambient air temperature). The winter burns were conducted the first winter after tebuthiuron application and after natural leaf shed associated with dormancy. Immediately before each plot was burned, air temperature and relative humidity were measured with a standard sling psychrometer. Average wind speed at 2 m was measured with a totalizing anemometer. In 1988, procedures were developed and data collected on two plots. Data were collected in 1989 on all combinations of treatments and data were collected on late summer burn plus tebuthiuron treatments in 1991 (Table 1). Treatments were applied in a completely randomized design with a variable number of replications.

Table 1. Descriptions of treatments used in a study of leaf-litter fires in the cross timbers of northcentral Oklahoma.

Year	Treatments: Burn season	Treatments: Herbicide	Number
1988	Late summer	Tebuthiuron	1
		None	1
1989	Late summer	Tebuthiuron	4
		None	4
	Winter	Tebuthiuron	4
		None	4
1991	Late summer	Tebuthiuron	4
Total			22

Fuelbed Characteristics

Fuelbed characteristics were sampled for each treatment plot immediately before the assigned burn treatment. Fuel load was measured by harvesting fuel components within 5 quadrats (0.5 X 0.5 m) placed at random, but restricted to within 3 m of plot edges to minimize disturbance to the fuel bed within the center of the plot. Material within each quadrat was separated into 1-hr time-lag fuels (primarily downed deciduous leaf litter and downed woody debris ≤0.64 cm in diameter and small amounts of green herbaceous, standing herbaceous litter, downed herbaceous litter), and 10-hr time lag fuels (downed, woody debris between 0.65 and 2.54 cm in diameter) (Nelson 1969). Fuel load components were weighed in the field, oven-dried at 70° C, and then reweighed to obtain fuel moisture on an oven-dry weight basis. Depth of the fuelbed, defined as the vertical distance from the bottom of the leaf-litter layer to the highest dead particle in the sampling plane (Brown 1974), was measured at 5 random locations within the plot.

Fire Behavior and Fire Effects

Fireline intensity (*I*), defined as the rate of energy or heat release per unit time per unit length of fire front, was calculated using the equation $I = Hwr$ (Byram 1959, Alexander 1982). The fuel load heat content (low heat of combustion, *H*) was obtained by adjusting high heat of combustion for fuel moisture and heat of vaporization. High heat of combustion, 17,300 kJ kg^{-1}, was calculated from data taken from similar fuels in southeastern Oklahoma (Masters and Engle 1994). Fuel consumption (*w*) (considered equal to fuel load if combustion is complete) was incomplete, so fuel loading was adjusted by post-burn sampling of unburned residue in 5 quadrats (0.5 X 0.5 m) per plot placed at random. Forward rate of spread (*r*) was estimated by timing passage of the fire front between two points marked with metal rods within the fuelbed. Heat per unit area (*HA*), the total energy or heat released per unit area, was calculated by dividing *I* by *r* (Rothermel and Deeming 1980).

Eastern redcedar crown scorch and tree kill were estimated visually 60 days post-burn on all trees of three size classes: trees less than 1.5 m in height, trees 1.5 to 2.5 m in height, and trees 2.5 to 5.0 m in height. Trees with 100% crown scorch, to include crown consumption by fire, were considered to be killed by the fire.

Statistical Analyses

To determine the influence of tebuthiuron and burn date on fuelbed characteristics, fire behavior, and fire effects (crown scorch and tree kill), the data were subjected to one-way analysis of variance. Because the design was unbalanced, we used the Type I sum of squares in the SAS PROC GLM (SAS Institute Inc. 1988). The least significant difference test protected by a significant ($P<0.05$ or $P<0.10$) F-test was used to separate differences in means when significant burn season by herbicide interactions were detected.

We used stepwise multiple regression to construct models of crown scorch when regressed against independent variables of fire behavior (i.e., fireline intensity, rate of spread, and heat per unit area). We used stepwise discriminant analysis to find the subset of fire behavior, fuelbed condition, and weather variables that best revealed differences among successful and unsuccessful fires, defined as those fires that scorch <75% of small trees (SAS Institute Inc. 1988). Exploratory analysis of the data indicated a curvilinear relationship between fireline intensity and crown scorch, so we included the natural log of fireline intensity as an independent variable.

Results and Discussion

Fuelbed Characteristics, Weather Conditions, and Fire Behavior

Two of the three highest intensity fires occurred in 1988. Precipitation was lower than average in June through August of 1988 (Table 2), which resulted in a dry, loosely-arranged fuelbed Above average precipitation for May through August before the late-summer

Table 2. Growing-season precipitation during the study years and average growing-season precipitation at Stillwater, Oklahoma.

	(mm)			
	1988	1989	1991	Long-term average
Jan	36	42	25	28
Feb	9	43	02	32
Mar	139	95	25	56
Apr	104	4	80	85
May	69	172	179	123
Jun	33	139	102	102
Jul	68	112	11	77
Aug	25	128	36	76
Sept	198	123	145	95
Oct	40	72	108	71
Nov	88	0	69	52
Dec	24	13	130	34
April-Aug	299	555	408	463
Total for year	830	943	910	831

Table 3. Fuelbed conditions associated with treatments in studies of the effects of tebuthiuron on understory fuelbeds in the cross timbers of northcentral Oklahoma.

Treatments		Fuel loading				Fuel moisture		
Burn season	Herbicide	1-hr	10-hr	Consumed	Depth	1-hr	10-hr	Total
		(kg m^{-2})			(cm)	(%)		
Late summer	None	0.61bc[1]	0.16	0.27	3.4c[2]	12	16	12
Winter	None	0.91ab	0.26	0.30	7.6a	29	40	30
Late summer	Tebuthiuron	1.15a	0.30	0.57	5.5b	12	22	11
Winter	Tebuthiuron	0.83b	0.15	0.14	6.5ab	32	34	32
		Observed Signficance Level						
Herbicide		0.0154	0.6021	0.3852	0.4650	0.7053	0.9064	0.6345
Burn season		0.7191	0.6724	0.2377	0.0057	0.0006	0.1444	0.0001
BXH		0.0186	0.2654	0.2240	0.0588	0.7752	0.6290	0.7672

[1]Means in the same column followed by different letters are different ($P<0.05$).
[2]Means in the same column followed by different letters are different ($P<0.10$).

1989 fires, and to some extent before the late-summer 1991 fires, resulted in more litter decomposition and a wetter, more compact fuelbed.

Tebuthiuron-treated plots contained almost twice the 1-hr fuel loading as untreated plots burned in late summer (Table 3). Furthermore, fuel depth on untreated plots burned in late summer was about half that of other herbicide treatment and burning date combinations. However, fuel loading did not differ between tebuthiuron and untreated plots burned in winter, and fuel consumption did not differ among treatments. Moisture content of 1-hr fuels on plots burned in winter was more than twice that of 1-hr fuels on plots burned in late summer. Except for air temperature, which was much higher in late summer, weather conditions differed little between late summer and winter fires (Table 4).

Fuel loading in untreated plots was highest after natural leaf fall accelerated with dormancy. Johnson and Risser (1974) noted that leaf-litter standing crop begins accumulating in late July with seasonal drought and peaks in fall after the first freeze and again in March and April when leaf buds activate. The best fuelbed conditions, i.e. heavy fuel loading and dry, noncompacted leaves, in our studies occurred in late summer after tebuthiuron treatment. This resulted from a combination of the augmented leaf fall induced by tebuthiuron and good drying conditions typical of late summer. Should a manager desire to burn the understory leaf layer for eastern redcedar control before application of tebuthiuron for hardwood control, however, the burn would need to be conducted during dry weather after the normal autumnal leaf fall.

We have attempted spring burning of leaf litter under closed forest canopies with limited success because of decomposed or wet leaf litter. In contrast, natural grasslands managed for cattle in the Central U.S. are effectively burned in the spring. Frequent rainfall events, poor drying conditions caused by shading and low winds, and poorly structured fuelbeds are major limitations to spring burning of forest leaf litter. Low fine fuel load and a low proportion of dead to green fine fuel prevented continuous fire fronts, resulted in disappointing levels of control of overstory eastern redcedar in a study in the cross timbers of Oklahoma after tebuthiuron applications (Stritzke et al. 1991).

Managers should consider controlling understory eastern redcedar before applying tebuthiuron with a fire during dry weather after the normal autumnal leaf fall. This would increase the probability of obtaining a successful burn because burning could be delayed until winter burning conditions were favorable. In contrast, burning after application of tebuthiuron must be conducted in the late summer through winter immediately following tebuthiuron application. If good burning

Table 4. Weather conditions immediately before fires in a study of the effects of tebuthiuron on understory fires in the cross timbers of northcentral Oklahoma.

	Late summer fires (n=14)				Winter fires (n=8)			
Variable	Min	Max	Mean	SE	Min	Max	Mean	SE
Relative humidity (%)	28	55	44	2	21	47	35	3.3
Ambient air temperature (°C)	17	32	24	1	3	9	6	1
Wind speed (km hr^{-1})	0	0.9	0.4	0.1	0.1	0.9	0.4	0.1

Table 5. Behavior of fires associated with treatments in a study of the effects of tebuthiuron on understory fuelbeds in the cross timbers of northcentral Oklahoma. Standard errors are in parenthesis.

Treatments		Spread rate	Intensity	Heat per unit area
Burn season	Herbicide			
		(m s^{-1})	(kW m^{-1})	(kJ m^{-2})
Late summer	None	0.005 (0.002)	54 (49)	4532 (3035)
Winter	None	0.007 (0.001)	41 (17)	4922 (1720)
Late summer	Tebuthiuron	0.010 (0.003)	104 (42)	9774 (4046)
Winter	Tebuthiuron	0.006 (0.002)	10 (2)	2305 (753)
		Observed Significance Level		
Herbicide		0.2314	0.4531	0.3760
Burn season		0.3953	0.1319	0.2237
BXH		0.2292	0.2850	0.2310

conditions do not occur, then it will be several years before sufficient fine fuel accumulates to conduct a successful burn. By this time eastern redcedar will be too large to be adequately controlled by fire (Engle et al. 1991, Stritzke et al. 1991).

Fire behavior was highly variable in these burns, and no differences in measures of fire behavior were detected among treatments (Table 5). Even though late summer fires tended to be more intense than winter fires ($P<0.1319$), fire intensity was very low on all 22 fires. Heat per unit area was comparatively higher than fireline intensity because of slow rates of spread, and was similar to that of fires in tallgrass prairies in this same ecoregion. Fires in tallgrass prairie with fine fuel loading similar to those in this study commonly have fireline intensities over 1000 kW m^{-1} and heat per unit area of 5,000 to 10,000 kJ m^{-1} in summer and spring (Bidwell and Engle 1992, Engle et al. 1993).

Because fuel load in these studies (Table 3) was the most variable parameter in Byram's (1959) fireline intensity model, we expected fireline intensity to have varied much more among treatments, with the late-summer fires in tebuthiuron-treated plots burning more intensely than other treatments. However, fuel consumption, the variable we used for w to calculate fireline intensity, did not differ among treatments.

Crown Scorch and Tree Kill

Despite the less than ideal fuelbed conditions and low fire intensities in these studies, and especially in the studies of 1989 and 1991, crown scorch and kill of small trees was 83% or higher on all but the late summer-no tebuthiuron treatment (Table 6). Since the density and competition potential of small trees is often the highest of the three size classes, the level of control on small trees achieved on these three treatment combinations is important in terms of reducing the influence of eastern redcedar on the post-tebuthiuron vegetation. Crown scorch and kill of large trees were greater on late-summer burn treatments as an average compared to winter burn treatments, and crown scorch of large trees was greater on tebuthiuron treatments than plots not treated with tebuthiuron.

Table 6. Fire scorch and mortality of three size classes of eastern redcedar in plots with no herbicide or treated with tebuthiuron and either burned in late summer or winter in the cross timbers of northcentral Oklahoma.

Treatments		Crown scorch			Tree kill		
Burn season	Herbicide	Small	Medium	Large	Small	Medium	Large
			(%)			(%)	
Late summer	None	71b[1]	54b[2]	39	52b[1]	41a[1]	27
Winter	None	92a	81a	30	87a	62a	0
Late summer	Tebuthiuron	91a	80a	66	84a	59a	35
Winter	Tebuthiuron	88a	49b	34	83a	22ab	0
		Observed Signficance Level					
Herbicide		0.1349	0.6361	0.0821	0.0755	0.8642	0.4827
Burn season		0.2497	0.5897	0.0717	0.1157	0.5206	0.0268
HXB		0.0970	0.0114	0.3550	0.0614	0.0929	0.7721

[1]Interaction means in the same column followed by different letters are different ($P<0.10$).
[2]Interaction means in the same column followed by different letters are different ($P<0.05$).

As with grassland fires, crown scorch and tree kill were tree-size dependent, with a greater proportion of smaller trees killed than larger trees. Twenty to 50% of large eastern redcedar trees are not killed in moderate intensity grass fires (Martin and Crosby 1955, Engle et al. 1988), whereas almost all small trees are killed by a single broadcast fire in grasslands of the central U.S. (Wright and Bailey 1982, Rollins 1985, Engle et al. 1988). Fine fuel loading and fine fuel continuity are the primary factors influencing crown scorch and tree kill of eastern redcedar in grasslands (Rollins 1985, Engle et al. 1988). Our data indicate that given adequate, dry fuel, high levels of small eastern redcedar can be killed with winter or summer burns following tebuthiuron treatments within the hardwood types of the central U.S.

Fireline intensity is related to fire effects above the flame zone in conifer stands (Albini 1976). Height of lethal crown scorch in conifers (Van Wagner 1973) and topkill of stems and branches of savannah trees and shrubs (Trollope 1984) have been related to fireline intensity. Fireline intensity is a good indicator of the degree to which the tree crowns are exposed to direct flames and hot convective gases above the flame (Rothermel and Deeming 1980). Indeed, the regression analyses indicated that of the three fire behavior measures, fireline intensity, rate of spread and heat per unit area, fireline intensity (or its natural log) was the only fire behavior variable selected in stepwise regression of crown scorch (R^2 = 0.28, 0.35, and 0.61, for small, medium, and large trees, respectively, $P<0.05$, $df=21$). Some researchers have reported that the thin bark of eastern redcedar may expose the cambium to heat damage (Dalrymple 1969, Wright and Bailey 1982, p. 94). Should this be true, fires of low fireline intensity may not provide immediate crown scorch but may kill trees by damaging the cambium tissue at or near the soil surface. Tree damage from cambium injury was probably not accounted for in our data since we measured crown scorch 60 days after burning.

Fireline intensity is the most important fire behavior variable explaining the success of the fires in terms of crown scorch of small trees according to discriminant analysis. The natural log of fireline intensity explained about 47% of the variation in fire success ($P<0.0006$) and ambient air temperature explained an additional 19% of the variation in fire success ($P<0.0468$). Albini (1976) provided graphs derived from Van Wagner's (1973) equations for height of crown scorch versus Byram's fireline intensity for various wind speeds and air temperatures. The graphs demonstrate that height of crown scorch increases with increasing air temperature. In contrast, higher wind speeds sharply decrease scorch height, which is somewhat counter intuitive since Byram's fireline intensity usually increases rapidly with wind speed. Even when winds in nearby prairie openings are high, winds in these hardwood forests are usually light and variable in direction, so we did not expect wind speed to be a significant variable explaining fire success. Although these normally low wind speeds expand the prescription window for burning, the slow flame-level wind speeds and resulting slow rates of spread (Table 5) also expand the amount of time necessary to complete ground-ignited prescribed burns in these forests.

Conclusions

Treatment of cross timbers sites with tebuthiuron for control of hardwoods will effectively augment leaf-litter fuel load and provide a suitable fuelbed for burning by late summer. Except for large trees, crown scorch and tree kill are not greatly reduced by burning in winter as compared to late summer. However, burning must be conducted in the year of tebuthiuron treatment, otherwise leaf-litter fuelbeds deteriorate and will not burn. If most of the understory eastern redcedar are less than 1.5 meters tall, then managers should consider burning in fall or winter in natural leaf fall litter fuelbeds before application of tebuthiuron. On the other hand, if managers prefer to maximize the kill of large trees, they should burn in late summer after treatment of tebuthiuron. Regardless of timing, burning in leaf litter fuelbeds gives managers in the cross timbers and similar vegetation types an effective means of controlling fire-sensitive woody species.

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