ARTICLE IN PRESS
JID: RAMA [mUS5Gb;August 22, 2024;20:16]

Rangeland Ecology & Management xxx (xxxx) xxx

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: www.elsevier.com/locate/rama

Original Research

No Field Evidence of Grass Fuel Structure effects on Postfire Tree Mortality in *Juniperus virginiana* ☆

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ARTICLE INFO

Article history:
Received 16 November 2023
Revised 2 July 2024
Accepted 24 July 2024
Available online xxx

Key Words:
Eastern red cedar
Fuel structure effect
Postfire tree mortality
Prescribed fire
Tallgrass prairie
Woody plant encroachment

ABSTRACT

Prescribed fires are an important management tool for containing woody plant encroachment in rangeland ecosystems. Grasses are the dominant fuel type in rangelands. Past work has shown that grass canopy architecture, which varies among grass species, can influence flammability. Whether variation in grass fuel structure can influence postfire plant responses has not yet been tested. To bridge this gap, we set up field burning experiments with different fuel treatments and examined postfire mortality of *Juniperus virginiana* L. in a tallgrass prairie in southwestern Missouri. We sampled 60 trees and measured tree height and diameter at breast height before the fire. Fuels surrounding each tree were manipulated to vary independently in both fuel load and fuel structure. Flame temperatures were measured during the fire, and both stem and canopy injuries were evaluated 1 d after the fire. We surveyed tree mortality 7 mo after the fire. We found no effects of either fuel load or fuel structure on postfire mortality or on canopy injury in *J. virginiana*. Canopy injury was a critical fire severity measurement determining postfire mortality in *J. virginiana*, and taller trees are more fire resilient. Despite laboratory-observed fuel structure effects on flammability, this study finds no evidence for the importance of grass fuel load and canopy architecture in influencing postfire tree response. This result might arise from the low crown depth and low canopy water content of *J. virginiana*, which can promote canopy fire and result in a high mortality rate across fuel treatments. Notwithstanding the negative results, testing laboratory-based findings in field settings is important for further examining laboratory observations and upscaling individual-level processes to ecosystems to help identify the key ecological processes determining population dynamics and community assembly. Our study also suggests that prescribed fire is an effective tool to remove encroaching *J. virginiana* in tallgrass prairies at an early stage.

Introduction

Native to the eastern United States, *Juniperus virginiana* L. has significantly expanded its range in the central United States during the last 5 decades. One effective management practice to control encroachment of *J. virginiana* in native grasslands is prescribed fire. *J. virginiana* is one of the most widely spread native tree species, with a distribution from the eastern Great Plains to the Atlantic coast (Harper 1912). Due to altered land-use management such as fire suppression and intensive grazing (Briggs et al. 2002a), *J. virginiana* has expanded its distribution into mesic tallgrass prairies across the central United States at the expense of native prairie species (Gehring and Bragg 1992; Briggs et al. 2002a; Knapp et al. 2008; McKinley et al. 2008). As a nonresprouting juniper, *J. virginiana* is susceptible to fire and is often managed with prescribed burning (Ortmann et al. 1998; Ansley and Rasmussen 2005). The effectiveness of prescribed fires in removing encroaching woody plants depends on various factors, including the fire-resistant traits of the targeted species and local fuel characteristics (Ryan and Noste 1985; Sparks et al. 1999; Fuhlendorf et al. 2011). Postfire tree mortality in nonresprouting junipers often decreases with tree size as mature trees are more fire resilient than saplings (Ortmann et al. 1998; Noel and Fowler 2007; Clark et al. 2018). The probability of fire-induced tree mortality also decreases as the age of the stand increases because of the significantly reduced

☆ This work was supported by internal funding from the Dept of Biological Sciences at Missouri University of Science and Technology.
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https://doi.org/10.1016/j.rama.2024.07.012
1550-7424/

fine fuels underneath the tree canopies (Briggs et al. 2002b; Twidwell et al. 2013). Previous work has examined fuel load effects on postfire mortality in nonresprouting junipers (Bryant et al. 1983; Twidwell et al. 2009; Clark et al. 2018), but no study has explored the potential effects of fuel characteristics (e.g., grass canopy architecture) on fire impacts. Understanding this subject is important for planning prescribed burns to meet management goals.

Variation in species-specific traits can alter fire behavior, which in turn influences postfire plant response. Plant traits determine flammability (Schwilk 2003; de Magalhães and Schwilk 2012; Engber and Varner 2012; Simpson et al. 2016), and fire behavior metrics such as heat release influence postfire plant mortality (West et al. 2016; Bowman et al. 2018). Community composition and structure in fire-prone ecosystems are susceptible to changes in local fire regimes, which in turn feeds back to influence fire behavior and fire impacts (Harris et al. 2016; Archibald et al. 2018). Fire-mediated tree–grass interactions and the associated state transitions have been one of the major focuses in fire ecology studies (Scholes and Archer 1997; Van Langevelde et al. 2003; Staver et al. 2011). Past work often focused on mono-specific grass fuels or the effects of fuel load on fire behavior and postfire plant responses (Vilà et al. 2001; Rossiter et al. 2003; Bowman et al. 2014). Recently, a growing body of work has shown that both leaf morphology and canopy architecture can influence grass flammability at the individual plant level (Fill et al. 2016; Simpson et al. 2016; Gao and Schwilk 2018, 2022). In addition to laboratory observations, field experiments also show species-specific effects on grass fire behavior (Cardoso et al. 2018). Thus, it is possible that in ecosystems where grass species composition varies spatially, heterogeneity in grass fire behavior due to variation in flammability traits can result in different fire injuries in trees. A recent study indicated that grass biomass allocation in vertical space can influence heat release at different locations; for example, a bottom-heavy grass will release more heat at the soil surface while producing less heat at 50 cm above the ground (Gao and Schwilk 2018, 2022), which are important fire behavior metrics determining fire-induced mortality in tree saplings (Ryan and Frandsen 1991; Odion and Davis 2000; Butler and Dickinson 2010; Bowman et al. 2018). We thus set out to test if this canopy architecture effect on grass fire behavior can influence postfire tree mortality in the field.

In this study, we aimed to determine the independent and interacting effects of grass fuel load and fuel structure, namely, the proportion of total biomass allocated $>$ 30 cm above ground level, on postfire mortality in *J. virginiana*. To do so, we conducted prescribed burns where we experimentally manipulated both fuel load and fuel allocation in vertical space in a tallgrass prairie in southwestern Missouri. We examined fire injuries in sampled trees 1 d after the fire and determined the mortality rate 7 mo after the fire. We hypothesized that 1) fuel load will positively influence tree mortality rate and that 2) in addition to the fuel load effect, as more fuel is allocated $>$ 30 cm above ground level, there will be more heat released above ground, which will result in increased probability of tree mortality because of increased canopy injury.

Methods

Study site and prescribed fire

This study occurred at a tallgrass prairie site in the Springfield Plateau ecoregion (Baskin and Baskin 2000). The study site is 27 ha and is located on a private property, approximately 10 miles east of Lamar, Missouri (lat 37°29′37″N, long 94°16′20″W). Dominant grass species at the site include *Andropogon gerardii* Vitman, *Elymus canadensis* L., and *Panicum virgatum* L. Encroachment of *J. virginiana* is the main management concern at the study site and a primary issue for grasslands in Missouri and other south central region states in the United States (Baskin and Baskin 2000; Meneguzzo and Liknes 2015). To control further invasion by woody plants, prescribed fires were scheduled during daylight hours on December 13-14 2019. The study site was divided into three burn units (NE, SE, and SW units with a size of 7 ha, 10 ha, and 10 ha, respectively) by building fire break lines around each unit. All units had flat topography. The western unit was also invaded by *Lonicera japonica* Thunb., *Rubus armeniacus* Focke, and *Rhus glabra* L. Prescribed burns using ring firing techniques were applied to the two eastern units on December 13 2019, with two fires being separated by 4 h, and to the SW unit on December 14 2019.

Fuel treatments

Treatments varied both fuel load and biomass allocation in vertical space with a full factorial experiment design. Treatments were assigned randomly to individual trees (60 trees in total, 15 to each fuel treatment combination). To mimic native grass fuels, we used locally grown hay as the experimental fuel source. We used a 620 $g \cdot m^{-2}$ fuel load to represent average aboveground biomass in an annually burned tallgrass prairie (Abrams et al. 1986), and a 1240 $g \cdot m^{-2}$ fuel load to represent tallgrass prairies with high annual productivity (Kidnie 2009).The fuel structure treatment was meant to mimic variation in grass canopy architecture and included a low biomass height ratio (70% total fuel load was allocated below 30 cm height relative to the ground) and a high biomass height ratio (70% total fuel load was allocated above 30 cm height relative to the ground) to represent the extremes of canopy architecture measured in previous work (Gao and Schwilk 2018).

To manipulate fuel structure, we constructed a 0.5-m width $\times$ 1.0-m length $\times$ 0.3-m height fuel tray using wire mesh and placed it at a 30-cm height above the ground by wiring the tray to rebar posts at each corner. Three fuel trays were evenly spaced at the canopy edge of each sampled tree. Any existing fuels were cut to ground level and replaced by experimental fuels at fixed fuel loads. For the high biomass height ratio treatment, 70% of the total fuel load was set above the wire screen; for the low biomass height ratio treatment, 70% of the total fuel load was set on the ground. Fuels were spread to even depths at each location. We set up fuel treatments on the day of the fire to avoid disturbance and minimize variation in fuel moisture content across replicates.

Tree sampling and prefire measurements

To determine the effects of fire on trees, we sampled 60 adult individuals of *J. virginiana* (20 individuals per burn unit) and randomly assigned each to one of the four fuel treatments, with a total of 15 replicates for each treatment. Trees were randomly sampled throughout each unit by selecting individuals with heights varying between 1.5 m and 3.5 m. Selected individuals were separated by a minimum distance of 10 m to minimize spatial autocorrelation. Trees that recently experienced stress with visible signs or that were close to snags, logs, or within 10 m from the mowed firebreak lines were avoided during sampling. We tagged each tree and recorded the geographical location. Both tree diameter at 1.3 m above the ground and tree height were measured prior to the fire. However, we did not measure fuel moisture content of the sampled trees due to limited time and labor resources.

Fire behavior measurements

On the days of prescribed burns, we measured fire weather and fire behavior. Fire weather, including relative humidity, air temper-

Table 1
Weather information during each prescribed burning.

Burn unit	Date	Fire start time	Air temperature (°C)	Relative humidity (%)	Wind speed ($m \cdot s^{-1}$)
SE	2019-12-13	1355	16.7 ± 0.9	37.7 ± 2.6	0.9 ± 0.2
NE	2019-12-13	1810	5.1 ± 0.9	80.9 ± 9.2	0.4 ± 0.5
SW	2019-12-14	1140	3.2 ± 1.2	72.1 ± 7.2	1.6 ± 0.6

ature, and wind speed at 2 m above the ground, was measured prior to ignition and every 15 min during each fire using a Kestrel weather meter (Table 1). We measured flame temperature every second at the soil surface and 1 m above the ground by wiring one k-type thermocouple to the tree trunk at each location for each tree. However, we lost fire temperature measurements for half of the sampled trees accidentally.

Postfire measurements on fire severity and tree mortality

The day after prescribed burnings, we measured fire severity as tree bole char height, percentage of bole circumference scorched at 30 cm, and percentage of prefire crown volume scorched and loss (Catry et al. 2010; Peterson and Arbaugh 1986; Sieg et al. 2006). Tree bole char height was defined as the height relative to the ground where the blackened tree trunk due to scorching ended. We defined crown scorch as the portion of crown that was completely consumed or scorched by fire, while crown loss was defined as the portion of crown that was consumed only. Percentage of bole circumference scorched at 30 cm was defined as the percentage of bole circumference that was consumed or scorched by fire at 30 cm relative to the ground.

To estimate crown injury, we used both visual assessment and image analysis approaches. We first visually assessed the percentage of tree crown volume scorched by fire, and the measurement accounted for both tissue consumption and scorching. In addition, we took images of the tree crown after fire from four cardinal directions at fixed resolution (50 mm focal length), distance (5 m from the tree), and height (1 m above the ground). To include a scale reference for each image, we placed a metal ruler by the tree with the top 50 cm of length marked. To estimate tree crown volume before and after the fire, we manually defined the contour of each half of the prefire and postfire tree canopy in ImageJ (Rasband 1997), and extracted the coordinates of vertices defining the contour and the vertical axis of the canopy. The contour of the prefire tree canopy was defined by the plant skeleton left from the fire, assuming that the skeleton well represented the original shape of the canopy if only photosynthetic tissues and small twigs were combusted (Bond et al. 1990; Keeley et al. 2005). We defined postfire tree canopy as the portion of canopy with leaves still attached despite scorching. We then estimated the volume of the tree canopy using vertex coordinates of each half of the canopy contour (a closed, non–self-intersecting polygon) based on Pappus's centroid theorem (Goodman and Goodman 1969). Prefire and postfire tree canopy volumes were then calculated by averaging estimated volumes, and the percentage crown volume consumed was calculated by dividing postfire canopy volume by prefire canopy volume. We could not distinguish tissues that were scorched by fire from those that were not because of the cloudy and dim conditions under which photography occurred. Therefore, the image-derived crown injury measurement only assessed the percentage of tree crown volume that was consumed by the fire. Given there could be measurement error in both methods and the high correlation between the two crown injury measurements (correlation coefficient: 0.92), we conducted a principal component analysis on the two measurements and used the scores of the first principal component axis as the final crown injury index to determine postfire tree mortality.

To determine fire effects on trees, we examined tree survival status 7 mo after the fire in July 2020. An individual was marked as alive if any green tissue was present.

Data analysis

We first summarized flame temperature data by calculating the integrated temperature and heating duration at the soil surface and 1 m above the ground. Integrated temperature was defined as the sum of flame temperatures above 60°C over time during the fire (°C · s), and heating duration was the time duration during which flame temperatures reached 60°C or above (s). In addition, we extracted the peak temperature (°C) that was reached at each location. Fire temperature measurements were not included in further analysis due to the loss of some measurements, but summarized for each fuel treatment in Table 2 as they provide important information for field-scale fire behavior that might be of interest to other work.

Tree height and tree diameter at breast height were closely correlated, and both are positively related to bark thickness, which is a common heat isolation trait (Lawes et al. 2011; Schwilk et al. 2013). However, as tree height also indicates the chance of leaf tissue escaping the flame zone (Archibald and Bond 2003), we thus included tree height as a covariate in postfire tree mortality regression. As bole char height was closely correlated with crown injury, we selected bole circumference scorched at 30 cm above the ground as the stem injury measurement to determine fire-induced tree mortality.

To determine the effects of fuel treatments on postfire tree mortality, we applied an information-theoretic approach based on multiple hypotheses (Chamberlin 1965; Burnham et al. 1998). We first proposed a null hypothesis (H_0) in which we hypothesized that postfire tree mortality was influenced by location (a burn unit effect) and also negatively influenced by tree height. To examine the independent and interacting effects of fuel load and fuel structure on postfire tree mortality, we then proposed four alternative hypotheses: 1) postfire tree mortality was positively influenced by fuel load only (H_1); 2) postfire tree mortality was higher in the high biomass height ratio treatment without fuel load effect, which is due to increased heat release aboveground that can cause severer canopy damage (H_2); 3) there were additive effects of fuel load and biomass height ratio on postfire tree mortality (H_3); and 4) fuel load and biomass height ratio interacted with each other to influence postfire tree mortality (H_4). We built a logistic regression model corresponding to each hypothesis, and included tree height and burn units in all models (Table 3). We then calculated the corrected Akaike information criterion (AIC_c) given the small sample size (Richards 2005). The best model was selected according to relative AIC_c weights.

To confirm if there was any effect of fuel treatments on tree mortality, we built a linear model to determine fuel treatment effects on canopy injury. First, a logistic model was built to examine if measured canopy injury could predict postfire mortality in *J. virginiana* by including both canopy and basal stem injury measurements as predictors, and tree height and burn unit as covariates. A set of linear models was built according to proposed hypotheses that were as the same as hypotheses for postfire tree mortality, except the dependent variable was replaced by canopy injury

Table 2
Flame temperature measurements summarized for fuel treatments.

Fuelload	Fuel structure	Location (m)	Replicate	Duration (s)	Integrated temperature (°C)	Peak temperature (°C)
H	H	1	8	47.5 ± 56.2	6837.2 ± 12952.4	143.1 ± 191.8
H	H	0	8	128.0 ± 55.8	26477.7 ± 12320.8	487.4 ± 234.3
H	L	1	10	45.6 ± 40.8	6112.4 ± 7386.4	168.0 ± 164.3
H	L	0	10	145.8 ± 76.3	29556.9 ± 16846.4	426.6 ± 145.0
L	H	1	9	27.0 ± 47.7	4586.2 ± 11379.7	114.4 ± 182.3
L	H	0	9	104.5 ± 42.1	15965.8 ± 10462.7	270.5 ± 184.8
L	L	1	6	43.1 ± 34.9	4754.0 ± 5642.6	119.6 ± 76.6
L	L	0	6	113.8 ± 58.3	20819.9 ± 11772.8	307.3 ± 138.0

Each variable is presented by its mean and standard deviation. Location refers to where the flame temperature was measured relative to the ground. H: High fuel load (1240 g m^{-2}), or high biomass height ratio (70% of total fuel allocated above 30 cm height); L: Low fuel load (620 g m^{-2}), or low biomass height ratio (70% of total fuel load allocated on ground).

Table 3
Candidate logistic (linear) regression models for proposed hypotheses determining effects of fuel treatments on postfire tree mortality (Mortality) and canopy injury (Crown) with Akaike information criterion (AIC_c) for each candidate model provided.

Hypothesis	Logistic (linear) model	AIC_c mortality	ΔAIC_c mortality	AIC_c weight mortality	AIC_c crown	ΔAIC_c crown	AIC_c weight crown
H_0	**mortality (canopy injury) ~ burn unit + tree height**	26.66	0.00	0.45	64.02	0.00	0.39
H_1	mortality (canopy injury) ~ fuel load + burn unit + tree height	28.56	1.91	0.17	64.81	0.78	0.26
H_2	mortality (canopy injury) ~ biomass height ratio + burn unit + tree height	27.91	1.26	0.24	66.48	2.45	0.11
H_3	mortality (canopy injury) ~ fuel load + biomass height ratio + burn unit + tree height	29.90	3.24	0.09	67.35	3.32	0.07
H_4	mortality (canopy injury) ~ fuel load*biomass height ratio + burn unit + tree height	31.31	4.65	0.04	65.85	1.83	0.15

Best model is selected given the relative AIC_c weight and highlighted in bold. Selected best model is the null model for both postfire mortality and crown injury.

(Table 3). The best model was selected following the same procedure as described above.

Data analysis and figure making were conducted in R version 4.4.2 (Core R Team 2022) using R packages including the "car" (Fox et al. 2013), the "AICcmodavg" (Mazerolle 2020), the "Tidyverse" (Wickham et al. 2019), the "ggplot2" (Wickham 2011), and the "sjPlot" package (Lüdecke 2020). Numeric variables included in models were standardized to center around the mean to make the relative effects of variables comparable when necessary.

Results

Based on relative AIC_c weights, the null model was ranked as the best model to determine the effects of fuel treatments on both postfire tree mortality and canopy injury (Table 3). Therefore, there was no effect of fuel treatments on postfire tree mortality or on canopy injury. Across fuel treatments, postfire mortality was highest in the low biomass height ratio groups (55% mortality rate) for both high and low fuel load treatments; and lowest in the high fuel load with high biomass height ratio group (mortality rate 40%). The postfire mortality rate was 50% for the low fuel load with high biomass height ratio treatment. In addition, small-sized trees (height < 2 m) tended to have a high postfire tree mortality rate (> 80%); and the mortality rate dropped below 50% once the tree was taller than 3 m, especially for groups with 70% of the total fuel being allocated at 30 cm above the ground (Fig. 1). There was no unit effect on postfire tree mortality (Table 4). In contrast, measured canopy injury was similar across all sampled trees but higher in the NE unit compared with that in the SE and SW units (Table 4; Fig. 2). Indeed, canopy injury was an important fire severity measurement, and postfire tree mortality in *J. virginiana* increased in response to the increase in canopy injury (Table 5). Basal stem injury played no role in determining postfire tree mortality.

Discussion

We tested if grass fuel load and fuel allocation in vertical space would influence postfire mortality in *J. virginiana* by conducting field-scale burning experiments. Not only did we find no effect of fuel structure (mimicking biomass height ratio, a measure of grass architecture), in contrast to previous work (Twidwell et al. 2013; Clark et al. 2018), we did not find any effect of total fuel load on postfire tree mortality in *J. virginiana*. In past work, we found that grasses allocating more biomass near the ground produce more heat at the soil surface while generating less heat at 50 cm above the ground (Gao and Schwilk 2018, 2022). Given that even total fuel load had no effect on postfire mortality in our study, it is not surprising that we found no effect of a mimicked grass architectural trait. *J. virginiana* is a nonresprouting juniper for which canopy injury is the most critical fire severity measurement predicting its postfire response (Hood et al. 2007; Grayson et al. 2017). Indeed, we found that as canopy injury increased, there was a higher chance of mortality without any effect of stem injury. The lack of fuel load and fuel structure effect on canopy injury and postfire mortality in *J. virginiana* is possibly because trees sampled in this study were ready-to-ignite fuels at the time of fire, which can be a result of tree canopy traits including a low crown depth, a low canopy water content in winter, and the typically high content of flammable compounds in junipers (Yang et al. 2016; McCaw et al. 2018). In our study, it appears that combustion of the juniper canopy was insensitive to local grass fuel loads and that canopy consumption was a consequence of combustion of the juniper canopy itself. This seems to be a threshold effect sensitive to local fire behavior: once trees were exposed to enough heat, they could ignite and self-sustain the spread of fire within densely branched canopies, which resulted in a similar canopy injury across treatments. Such a threshold effect is also documented

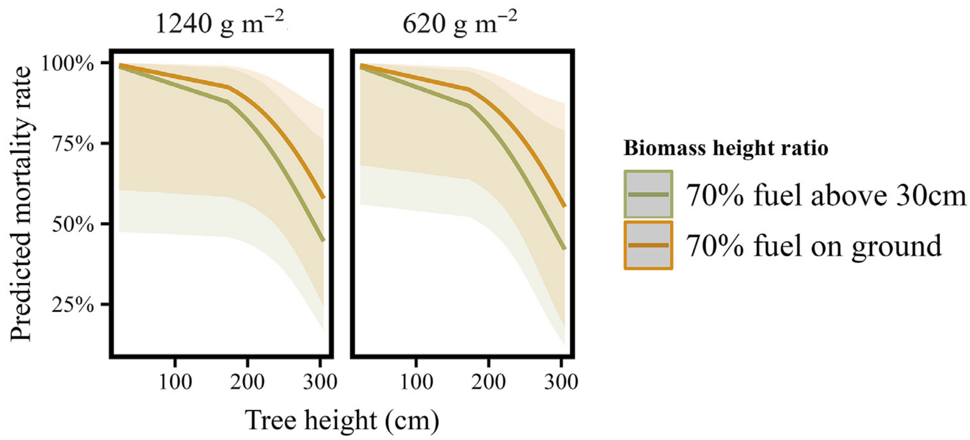

Figure 1. Predicted post-fire tree mortality using a logistic regression model including tree height, burning unit, and fuel treatments. Effects of fuel treatments and tree height are shown in figure. Lines are model means and shaded areas are the standard errors of the model prediction. 1240 g m^{-2} and 620 g m^{-2} refers to high and low fuel load treatment respectively.

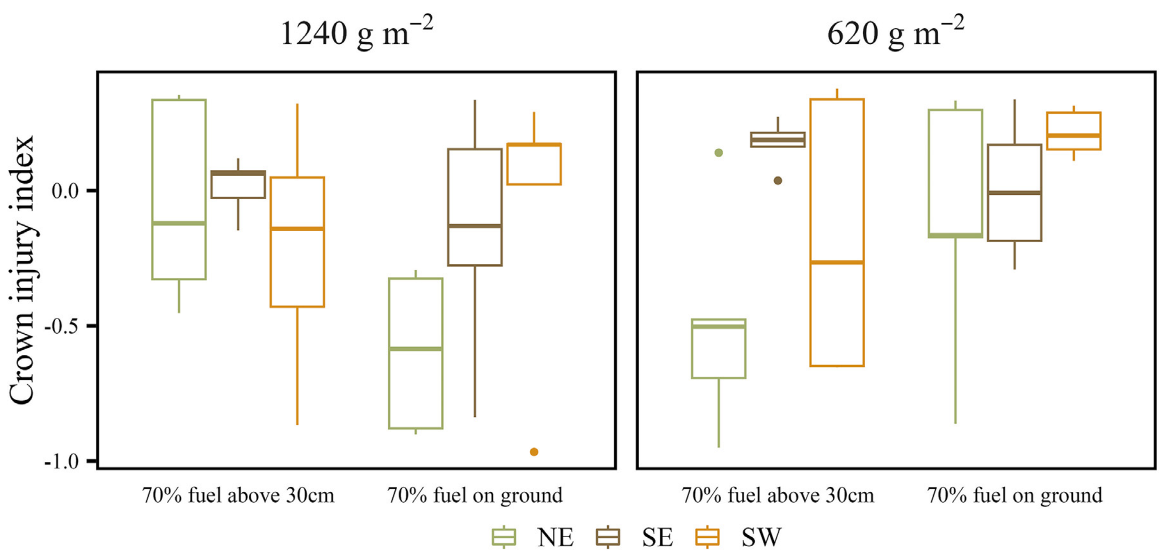

Figure 2. Fuel treatment effects on postfire crown injury. Crown injury index used was the scores of the first principal component axis from principal component analysis on the two crown injury measurements. As the value of crown injury index decreases, the measured crown injury increases. Box is color coded in unit to show unit variation in crown injury. 1240 g m^{-2} and 620 g m^{-2} refers to high and low fuel load treatment respectively.

Table 4
Coefficients and ANOVA table for the best models selected to determine effects of fuel treatments on postfire tree mortality and canopy injury.

	Postfire mortality				Canopy injury			
	Intercept	Tree height	Unit(SE)	Unit(SW)	Intercept	Tree height	Unit(SE)	Unit(SW)
Model coefficient	4.949	−0.016	−0.070	−0.729	−0.463	0.001	0.323	0.260
P value		0.038[1]	0.545			0.575	0.027[1]	
Degrees of freedom		1	2			1	2	
F value		4.515	0.613			0.319	3.861	

[1] Significant effects.

Table 5
Coefficients and ANOVA table for logistic model determining effects of canopy and stem injuries on postfire tree mortality.

	Canopy injury	Stem injury	Tree height	Unit(SE)	Unit(SW)	Canopy injury: stem injury
Model coefficient	−1.047	2.715	−1.357	1.017	−0.070	−2.156
P value	< 0.001[1]	0.449	0.003[1]	0.307		0.248
Degrees of freedom	1	1	1	2		1
F value	16.310	0.583	9.403	1.207		1.367

[1] Significant effects.

in the study by Twidwell et al. (2009), who found that high fuel load leads to increased crown scorch in juniper trees during the wet season, but 100% crown scorch is observed once the undercanopy fuel load exceeds only 0.128 kg m^{-2} during the dry season. In addition, canopy injury was more severe in the NE unit than in the two southern units. This might be explained by the fact that the NE unit was burned after sunset on the first day when temperatures were high and relative humidity was low during the day (Table 1), which together might contribute to a lower average fuel moisture content, intensifying the fire in the NE unit. Although, we did not measure fuel moisture content to confirm this hypothesis.

The high postfire mortality we found in this work suggests that prescribed fire can be an effective tool to remove and contain woody plant encroachment into grasslands, especially when targeted woody species are fire susceptible. Native grasslands with high biodiversity are important ecosystems, providing wildlife habitats and high-quality forage for livestock. As most grasses prefer open habitats with ample sunlight, periodic fire is an important ecological process that maintains grassland community composition and structure by suppressing woody plant cover (Perrings and Walker 1997; Mapiye et al. 2008; Gholami et al. 2020). Land-use change and the associated shift in fire regime have led to increased tree or shrub cover in grasslands across the Western and Central United States (Van Auken 2009; Brunelle et al. 2014). Management practices such as aerial herbicide application, mechanical treatment, and prescribed fires are common tools for removing trees and shrubs in grasslands (Scholtz et al. 2018). The cost associated with each of those management practices varies significantly, with prescribed fire usually being the most cost-efficient tool (Taylor et al. 2013). However plant responses to prescribed fires vary across species, which often requires managers to take into account factors such as fire-resistant traits of the targeted species, timing and type of prescribed fire, and local fuel characteristics (Ryan and Noste 1985; Mandle et al. 2011). The high postfire mortality we observed in eastern red cedar under both low and high fuel load treatment suggests that in tallgrass prairies where annual productivity is high, using prescribed fire to kill encroaching woody plants should not require additional fuel manipulations such as adding fine fuels. This, however, can change if sites are further invaded by woody plants with significantly reduced understory herbaceous cover (Clark et al. 2018); or eastern red cedar grows next to dense shrub populations on infrequently burned sites that the shrubs can act as a fire refugia to prevent fire-induced mortality even for small trees (Nippert et al. 2021). Therefore, active monitoring and detecting woody plant encroachment in combination with applying prescribed fires at the early stage of invasion should be an effective way to prevent grassland degradation caused by woody encroachment. The lack of a fuel structure effect on tree mortality in this work does not necessarily mean that local fuel characteristics are not important. Rather, it is important to consider both canopy and surface fuels when using prescribed fire as a management tool. The low canopy depth and high content of flammable compounds in eastern red cedar potentially promoted canopy fires by increasing both fuel continuity in vertical space and flammability. In systems where such ladder fuel is absent, considering other factors such as wind speed (e.g., relatively high wind speed instead of low wind speed) and topography (e.g., slope and aspect) can become important to make the prescribed fire more efficient in removing trees. On the other hand, managers should also consider minimizing the risk of management fires escaping into adjacent properties by mechanically thinning trees to prevent active crown fires when canopy fuel is highly flammable.

We examined the effects of fuel load and fuel structure on fire-induced mortality in *J. virginiana* by conducting field burning experiments. In conclusion, we found that neither canopy injury measured the day after the fire nor postfire tree mortality surveyed 7 mo after the fire varied by fuel treatment. This is consistent with criticisms of laboratory-based flammability trials as not representing real-world fire behavior (Fernandes and Cruz 2012; Resco de Dios 2023). However, given the absence of even a total fuel load effect on canopy injury or tree mortality, this result may simply demonstrate that the fire behavior during juniper canopy injury is insensitive to the grass fuels entirely. In this system, grass fuels may simply serve to carry fire between independently combusting trees. It is important to test laboratory-based observations in field settings in order to link the basic mechanisms to complex ecological processes. Our work also suggests that applying prescribed fires at the early stage of woody encroachment to remove fire-susceptible trees and shrubs can be an effective way to control further invasion by woody species in grasslands.

Management Implications

Woody plant encroachment and the resulting impacts on biodiversity, regional water and carbon cycling, and fire dynamics are one of the main management concerns for rangeland ecosystems across the western and Central United States. The high mortality rate in eastern red cedar after management fire in our study indicates that prescribed fire can be an effective tool to remove encroaching woody plants in grasslands. However, to achieve the desired management outcome, managers should consider the following: 1) applying management fire at the early stage of woody plant encroachment to ensure enough fine fuel load for supporting fire spread across the management unit and that woody plants are still small and fire sensitive. For instance, a height of 2–3 m is a critical threshold size for eastern red cedar, below which postfire mortality can be $>$ 50%; 2) applying management fire in the dry or dormant season rather than in the wet season, as the lower vegetation water content in the dry season can result in more intense fire, thus increasing postfire tree mortality. Such fire is also less detrimental to native herbaceous plants when most species are dormant during the dry season; 3) ladder fuels, either from the build-up of standing grass fuels or the low-branching architecture of trees, can be important for promoting canopy fire that leads to top-kill of non-resprouting trees. Prefire mechanical thinning might be required to reduce the risk of management fire escaping, especially when canopy fuels are highly flammable.

Our study does not provide long-term monitoring data on postfire population dynamics. However, it is worth noting that postfire management, such as planting native herbaceous species and applying herbicides to remove invasive species (e.g., invasive annual grasses) and new recruitments from encroaching woody plants, can increase the longevity of any management fire effect. In addition, recurrent management fires are often required to maintain a healthy community structure for fire-dependent rangeland ecosystems.

Author Contributions

Xiulin Gao, Dylan W. Schwilk, and Robin Verble designed the study. Xiulin Gao collected and analyzed the data. X.G. wrote the first draft of the manuscript, Robin Verble, Dylan W. Schwilk, and Xiulin Gao edited the manuscript.

Data Statement

Data and code resulted from this work can be found at https://github.com/XiulinGao/field-burning.

Declaration of Competing Interest

The authors declare that there is no conflict of interest in the subject matter discussed in this manuscript.

Acknowledgments

We would like to thank Jerod Huebner for conducting the prescribed fires and helping with the experiment setup. We also thank James Allen, Leah Allen, Justin Hinson, and Lilly Germeroth for their help on prefire tree measurements and setting up fuel treatments.

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