EXTREME FIRE AND FUEL LIMITATIONS DRIVE

FIRE EFFECTS IN *JUNIPERUS* WOODLAND

By

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PREFACE

Restoration of grassland and savanna communities receives considerable attention from ecologists, natural resource professionals, and landowners. Removal of fire is a primary driver of the woodland progression in grassland and savanna systems, yet reintroduction of fire into these systems has failed to reverse woody plant dominance. Here I focus on the use of extreme fire as a restoration tool in a *Quercus* savanna heavily invaded by *Juniperus*. Although previous work has shown reintroduction of fire to be largely unsuccessful, the use of extreme fire is largely unexplored. The first chapter, "Influence of scale and heterogeneity in linking fuel measurements with fire intensity and fire effects," illustrates the shortcomings of traditional sampling techniques in analyses of fire behavior and fire effects within a heterogeneous environment. I go on to demonstrate the importance of spatial and temporal considerations in the sampling of fuels, fire behavior, and fire effects. The second chapter, "Probabilistic thresholds and the potential reversibility of juniper woodland communities using extreme fire," draws upon concepts from the first chapter to progress our viewpoint of fire as a tool in restoration. Specifically, I test ecological thresholds perceived to prevent grassland and savanna restoration from *Juniperus* woodland and identify the environmental conditions required to surpass those thresholds. My aim is to provide researchers and managers with a new framework for the study and application of fire in the restoration of grassland and savanna communities.

I am honored and privileged to have worked with a number of great professionals and am grateful for this opportunity to recognize their efforts, advice, and friendship. I must recognize "The Crew" at Texas A&M Experiment Station in Sonora. Nick, Terry, Erika, Robert, Trevlin, Jack, Colin, Brandon, and James, I appreciate your willingness and effort to support this research and to assist in pushing the limits of prescribed fire application and acceptance. I admire the unselfish and loving culture that yourselves and others on the Edward's Plateau provide. I will always rank Sonora, Texas, as my single favorite place to live. I also thank my colleagues at Oklahoma State for their friendship, especially Ray Moranz for his undying passion for the "little things" in life, particularly rainbows, wildflowers, and butterflies, Meg McLachlin for her smiles, her refreshing Colorado (or non-Midwest) attitude, and her ability to out-bowl most people in the graduate office, Luke Bell for his loyalty and refreshing Oklahoma (or traditional Midwest) attitude, Ken Nelson and Chad Cunningham for my home away from home, Ryan Limb for the many laughs and outrageous times, and Jay Kerby for his leadership, advice, willingness to take care of all the other graduate students, and especially for his great friendship. I look forward to spending greater time with you all in the near future. I am indebted to my advisor and members of my committee for the success of this project. I appreciate my time with Dr. Sam Fuhlendorf for his approach to research, his shared sense of humor, and his mentorship in research, golf, and life. Many of the concepts and ideas presented in this manuscript are undoubtedly the result of numerous conversations with Sam. I look forward to additional collaborations in the near future and will always remember my time at Oklahoma State fondly. I also thank Dr. David Engle, Dr. Karen Hickman, and Dr. Charles Taylor, Jr. for their reviews and guidance.

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CHAPTER I

INFLUENCE OF SCALE AND HETEROGENEITY IN LINKING FUEL MEASUREMENTS WITH FIRE INTENSITY AND FIRE EFFECTS

ABSTRACT

Spatial and temporal dependence among fuel, fire behavior, and fire effects has been overlooked largely by fire research in grasslands and savannas. Most fire studies base their findings on random sampling of fuels or seasonal analyses of fire effects. We characterized the consistency of these techniques for multiple prescribed fires conducted in the growing season. A random sampling method was compared to a technique that mapped the spatial variability of fuels across the area. In addition, a seasonal analysis of fire effects was compared to effects that were the result of the immediate fuel and weather conditions at the time of the burn. Our results show that traditional analyses of fire effects are inconsistent and lead to misleading interpretations of the mechanisms that influence fire effects. We conclude that random and seasonal analyses should be used only when studies are conducted at a homogeneous scale that limits variability in fire behavior.

Key words: fire intensity; fuel load; fuel moisture; heterogeneity; juniper scorch; random sampling. spatial scale; temporal scale; variation

INTRODUCTION

Recognition of pattern has received considerable attention in ecology, but the ability to relate pattern to process drives landscape research (Li and Wu 2004). Unfortunately, it is much more common within ecological studies to describe changes in pattern than to understand the importance of the process in landscape change (Risser et al. 1994). Fire effects analyses are classic examples of ecological investigations that rely heavily on a non-spatial sampling approach. Few studies attempt to link fire effects to fire behavior (Whelan 1995), and those that do characterize fire behavior have not thoroughly evaluated spatial and temporal relationships among fuels, fire behavior, and fire effects. The few studies that have integrated spatial sampling techniques have done so for pre- and post-wildfire evaluations of plant community change over broad spatial scales (e.g. Turner et al. 1999). However, descriptions of prefire and postfire patterns are mostly descriptive and fail frequently to consider variation in fire behavior. To our knowledge, no study has mapped fuel heterogeneity at a scale that considers variation in fire intensity so that spatial and temporal variation in fire effects can be determined.

Perhaps the most alarming aspect of fire research is that field sampling methods have yet to incorporate methodological advancements developed in landscape ecology to assess spatial and temporal dynamics in fire effects. The standard fuels sampling approach is to measure fuel characteristics (e.g. fuel load) in small quadrats at random locations within a burn unit. Results are then extrapolated to represent the mean value for the entire area. Ultimately, this mean fuel estimate is related to mean assessments of fire behavior and/or fire effects (e.g. Bidwell and Engle 1992, Engle and Stritzke 1995, Hoch et al. 2002, Streeks et al. 2005). However, no study has rigorously tested whether or not this approach is a valid means of relating fuels to fire behavior and fire effects in a heterogeneous environment. If in fact random sampling of fuel characteristics are inappropriate, this technique could be a major source of contradiction within the literature and the root of much uncertainty associated with fire effects research.

The purpose of this study was to explore spatially and temporally variable relationships among fuels, fire behavior, and fire effects. We evaluated various fuel sampling strategies and compared their potential to predict fire effects on juniper. We designed a spatial sampling strategy that mapped fuel loads across the burn unit, and then related fire effects on juniper to the fuel load that occurred at various spatial scales. This type of design aims to link pattern to process, which is the cornerstone of landscape ecology and similar to the type of design used to model fuels and fire spread (Vasconcelos and Guertin 1992, Clarke et al. 1994, Gardner et al. 1999, Hargrove et al. 2000, Berjak and Hearne 2002). We compared this approach to the standard field sampling technique by collecting fuel load at random. We hypothesize fire effects on juniper are driven by local variability in fuel load and fire behavior that occurs at a scale relative to that of the observed effect. We use our findings to illustrate the importance of considering scale and heterogeneity when linking fuels, fire behavior, and fire effects in field research.

METHODS

Study Area

This investigation was conducted at the Texas A&M University Agricultural Experiment Station located near Sonora, Texas, on the Edwards Plateau (Hatch et al. 1990). Mean annual precipitation is approximately 600 mm but has varied from 156 mm to 1054 mm over the past 90 years. The site experiences bimodal distribution of precipitation in the spring and fall with frequent prolonged summer drought. Herbaceous vegetation, composed primarily of mid- and short-grasses, dominates the fuel bed. Continuity of the fuel bed is disrupted as the dominance between drought tolerant and intolerant species shifts in response to episodic summer drought.

Herbaceous continuity is disrupted further by the heterogeneous mixture of soil depth, rock outcrops, and woody encroachment (Fuhlendorf and Smeins 1998). Soils formed from Tarrant stony clays, classified as Lithic Haplustolls, are generally 15 – 30 cm deep and include frequent limestone outcrops (Wiedenfeld and McAndrew 1968, Fuhlendorf and Smeins 1996). Clusters of woody species, *Juniperus ashei, Juniperus pinchotii, Quercus virginiana, and Quercus pungens*, create a savanna that limits the accumulation of herbaceous vegetation under the woody canopy.

Design and Analysis

Juniper canopy cover and fuel load were measured along permanently established 50 m transects. Juniper cover was measured using the line-intercept method. Fine fuel loads were estimated within 0.25 m^2 quadrats at 0.5 m intervals for the length of the transect by classifying fuel four fuel load classes (FLCs = 0, 1, 2, and 3). Fuel load classes (FLCs) were developed to prevent destructive sampling and alteration of fire behavior. FLCs were calibrated on nearby areas by visually estimating fuel load within a 0.25 m^2 quadrat and comparing that estimate to the actual fuel load by clipping (n = 50). This technique accurately predicted the actual fuel load ($r^2 = 0.90$, $P < 0.0001$). Fuel loading (mean $\pm$ SE) of

10.7 $\pm$ 1.2, 97.8 $\pm$ 3.6, 220.3 $\pm$ 5.3, 406.2 $\pm$ 10.2 (g/m^2) represented FLCs of 0, 1, 2, and 3, respectively.

Nineteen independent ignitions were set in the growing season using 10 m wide headfires at the beginning of each transect. We selected two fire events with contrasting fuel moisture levels while attempting to minimize differences in all other fuel and weather variables (Table 1). Fourteen fires were ignited over the coarse of two days during a wet period of the summer. Another set of ignitions (n = 5) were set in one day during an extended dry period of the summer. Fuel moisture was measured on a dry-weight basis by clipping 0.25 m^2 quadrats in areas adjacent to each transect. Temperature, relative humidity, and wind speed were measured at a height of 1.5 m and a distance of 30 m downwind at the time of ignition. Although we attempted to conduct burns under similar weather conditions between fire events, some small but statistically different means were detected (Table 1). Relative humidity was approximately 5% higher in the second set of fires, whereas wind speed was approximately 4 km/hr lower. These differences are not likely to cause substantial differences in fire intensity (calculations can be performed from equations provided by Rothermel 1983) especially in light of the large differences in fine fuel moistures between the two events. Fuel moisture can range from 0% in completely cured fuels to the level of moisture extinction in live herbaceous fuels (de Groot et al. 2005 provide a value of 27.8%). Fine fuel moisture was on both ends of this spectrum in this study (Table 1). Thus, we primarily attribute differences in fire effects between fire events as a function of fuel moisture.

Fire effects on juniper were assessed for trees along each transect. Only juniper trees located along burned sections of the transect were included in this analysis. Numerous transects only partially burned and some did not burn at all, and consequently reduced the sample size considerably (n = 17 juniper trees). Of the 19 independent 10 m ignitions, only 4 burned the entire length of the transect. Most (n = 10) burned a portion of the transect before stopping, while some (n = 5) did not spread at all after ignition.

Juniper crown scorch was assessed two weeks following each fire by estimating the volume and height of scorch on the crown of each juniper tree. Although fire intensity was not measured directly, scorch height can be used as an estimate of fire intensity (Van Wagner 1973, Rothermel and Deeming 1980, Engle and Stritzke 1995, Williams et al. 1998). We estimated scorch volume and height as proportions (%) (Equation 1)to account for variable tree heights observed in this study (range = 1.0 to 4.5 m). A measure of scorch height in meters, as done traditionally, was incapable of assessing fire effects accurately in this study since trees of all sizes were scorched completely. In this case, the height of the tree limited the potential scorch height on the crown, regardless of fire intensity. For example, if 1.5 m and 4.5 m trees were scorched completely, the fire intensity that caused the effect on the 1.5 m tree may have been sufficient to induce scorch height equal to that of the 4.5 m tree. We compared the different types of measurements, scorch height as a proportion and in meters, and found that proportion scorch height reduced the total amount of error among samples in this study.

$$\text{Scorch height} = [\text{maximum scorch height (m)} / \text{tree height (m)}] \times 100\% \qquad \text{(Eq. 1)}$$

The relationship between fuel load and crown scorch was used to compare random and variable scaled fuel sampling techniques (Table 2). We developed a random sampling design that was similar to techniques typically applied in studies of prescribed fire by measuring fuel loads at random locations and extrapolating the results to represent the mean fuel load of the entire area (e.g. Bidwell and Engle 1992, Engle and Stritzke 1995, Hoch et al. 2002, Streeks et al. 2005). Quadrats were selected randomly along the transect (n = 10) using Monte Carlo simulation and quadrats were averaged to obtain the mean fuel load for each transect. Simulations were repeated 1500 times for each transect. Correlation between the mean random fuel load and juniper crown scorch was produced for each simulation, resulting in 1500 total correlations. Variability between correlations was analyzed to determine the repeatability of a random sampling design.

To identify the role of spatial scale of measurement on the relationship between fuel load and juniper crown scorch, fuel loads were described at multiple spatial scales. Spatial scales were chosen in two ways. First, fuel load along the line was classified by aggregating the attributes of individual quadrats (0.25 m^2) for arbitrarily selected spatial scales of 1.0 m, 5.0 m, and 10.0 m from the canopy midpoint of each juniper tree. Fuel load at each scale was subsequently related to juniper canopy scorch. The second spatial technique differed from the first approach in that fuel load was related to each juniper crown more functionally instead of at an arbitrarily selected scale. This approach linked fuel load to variable crown sizes by aggregating quadrats along the transect that corresponded to the intercept of each juniper crown. Thus, only the fuel load that occurred beneath each juniper was related to crown scorch.

Correlation coefficients (*R*) produced with a scaled sampling strategy were compared to those produced for a randomized design to determine the most appropriate technique to sample fuel characteristics in relation to fire effects. The spatial scale that best predicted the relationship between fuel load and crown scorch were used for this comparison. Techniques were compared by the frequency with which random fuel load samples better predicted canopy scorch (i.e. produced a higher correlation coefficient) than that of a spatial sampling design. A probability of 0.05 was established to indicate whether or not a spatial sampling technique was superior. Relationships between fuel load and juniper scorch characteristics were analyzed using regression analysis. Comparisons among scales were assessed with two-way analysis of variance using the Bonferroni correction.

RESULTS

The relationship between fuel load and fire effects varied with scale of measurement when fine fuel moisture was 21% (Table 3). Variation in scorch height and scorch volume was explained best by fuel loads that were aggregated to the scale of the canopy intercept (R^2 = 0.876, $P < 0.01$, and R^2 = 0.789, $P < 0.05$, respectively). When comparing scorch height and scorch volume over multiple spatial scales, the strength of the relationship increased from the lowest scale (1.0 m) to a scale of 5.0 m, and subsequently decreased at the 10.0 m scale (Table 3, Figure 1a). Fuel loads summed to 5.0 m from the canopy midpoint was the only arbitrary scale significant for both scorch height and scorch volume ($P < 0.05$). Regressions were not significant ($P > 0.05$) for arbitrary measures of fuel load at the 1.0 m and 10.0 m scales for scorch height, and at the 10.0 m scale for scorch volume. Scale did not have a major effect on predicting fire effects when fine fuel moisture was low (Table 3, Figure 2b).

To determine which sampling technique (random vs. scaled) was most reliable in relating fuel loads to fire effects, correlations were compared for fuel loads that were sampled at random and at the scale of the canopy (because explanatory power, *R*, was greatest at the canopy scale compared to other scales; Table 3) for both sets of fires. Monte Carlo simulation results demonstrated that randomly sampled fuel loads inconsistently predict juniper crown scorch (Figure 1). Correlations (*R*) between canopy scorch and random fuel loads ranged from less than 0.01 to 0.955 for scorch height and less than 0.01 to 0.925 for scorch volume when fine fuel moisture was 21%, and from less than 0.01 to 0.796 for scorch height and less than 0.01 to 0.647 for scorch volume when fine fuel moisture was 4%. On average, randomly sampled fuel load was related weakly to juniper scorch for both fuel moisture levels (Table 4). Comparing these results to those produced by spatially referencing fuel loads to the canopy revealed that the spatial sampling technique was far more effective at predicting scorch (P = 0.001, Table 4).

DISCUSSION

We attribute the effects of fire on juniper in this study to spatial and temporal variation in fire intensity. Here we define spatial variation in fire intensity as local differences in scorch proportions that occurred within a fire, and temporal variation in fire intensity as differences in scorch proportions between fire events. We use this terminology because consideration of fire as a spatially and temporally variable process is lacking for field studies in fire research, as evident from the continued use of random sampling of fuel characteristics and seasonal analyses of fire effects. Recognition of spatial and temporal variation has considerably advanced research in other ecological sub-disciplines (Stenseth 1980, Dempster and Pollard 1986, Good et al. 1997, With 1997), and has become increasingly important in modeling fire spread (Kessell 1979, Vasconcelos and Guertin 1992, Clarke et al. 1994, Gardner et al. 1999, Hargrove et al. 2000).

An increased awareness of spatial and temporal variation may make comparisons between studies more appropriate (Pyne 1996), but current field assessments of fuels and fire behavior do not allow for this to occur. At the very least, methods need to be repeatable to make interstudy comparisons. Traditional, random sampling techniques were unable to produce consistent, repeatable results in this heterogeneous environment (Table 5, Figure 1). Within the first set of fires, correlations (R) ranged from less than 0.01 to 0.955 for scorch height and less than 0.01 to 0.925 for scorch volume. This means that two studies could be identical in fuel characteristics, fire behavior, and fire effects, yet still yield dramatically different results. Using our results, one study could find that juniper scorch was strongly related to fuel load (e.g. $R = 0.9$), while another could find that scorch was weakly related (e.g. $R = 0.1$). Even when fire effects were more uniform, as observed in the second set of fires, random sampling techniques continued to produce variable results (Figure 1b, Table 4). This suggests that random techniques are likely to be problematic, even in areas where fuel complexity is lower. Two reasons account for these contradictions. First, data collected at fine scales will often be misinterpreted when extrapolated to broader scales (Ricklefs 1987, McKenzie et al. 1996). This occurs in a randomized design when fuel loads are sampled within a given number of small quadrats (e.g. 0.5 x 0.5 m) and extrapolated to represent the mean fuel load of the entire area. Second, a random sampling technique relates the fuel load at one location to the intensity and effects at another location. This assumes that the fuel and fire intensity in both locations are the same (i.e. assumes homogeneity). This assumption is rarely, if ever, met in a heterogeneous environment.

A multiscale approach has been incorporated into many studies to alleviate potential problems that arise when analyzing process-pattern relationships within heterogeneous environments (O'Neill et al. 1989, 1991). Still, the manner in which scales are chosen continues to be debated in ecological studies. The general rule is to arbitrarily choose scales so that the minimum sampling unit is small enough to capture variability of the process, while the maximum sampling unit is of sufficient extent to constrain the overall process (Turner 1989). This was done in this study by relating juniper canopy scorch to the fuel loads that occurred at multiple spatial scales (1.0 m, 5.0 m, and 10.0 m from the canopy midpoint). The amount of variation in juniper scorch that was explained by fuel load increased from the 1.0 m scale to the 5.0 m scale, but then decreased from the 5.0 m scale to the 10.0 m scale (Figure 1, Table 3). This demonstrates that canopy scorch is dependent on the fuel that exists at some spatial proximity to the tree. Compared to other scales, a scale of 5.0 m most closely resembles the range of canopy sizes (1.5 – 6.0 m) that were recorded in this study (Figure 1, Table 3). Measures of fuel loads at a 1.0 m resolution failed to identify patches of fuel beneath the canopy that contributed to scorch characteristics (R = 0.447 for scorch height; R = 0.719 for scorch volume). Alternatively, broader scales (10.0 m) recognize patches of fuel that are not influencing the observed effects. At some distance, sufficient heat is not being transferred from the fuel source to the canopy.

Our results clearly demonstrate that random sampling techniques and seasonal analyses of fire effects are inappropriate. With these techniques, conclusions are often misleading and comparisons between studies are erroneous. Sampling techniques need to be developed that quantify spatially variable fuel characteristics, while relating these characteristics to fire effects at a scale that accounts for variability in fire intensity. We found the relationship between fuel load and fire effects on juniper were best described at the scale of the canopy (Table 3, Table 4). However, this does not mean that this is the appropriate scale for all assessments of fire effects on juniper. If fires were conducted in higher wind speeds, increased tilting of the flames would occur, and heat would be transferred for further distances. In this example, the fuel in front of the canopy would likely contribute to scorch effects as well.

CONCLUSIONS

Fire has been identified as a process that varies in space and time (Williams et al. 1994, Whelan 1995, Pyne 1996). This statement implies that fire is a dynamic process that varies in response to, but independent of, changes in pattern, similar to how an organism interprets its environment. In fact, changes in fire behavior are predictable responses to spatial and temporal heterogeneity in fuel, weather, and topography. The distinction we present here identifies fire behavior as a process that is directly dependent on variation in spatial and temporal patterns at multiple scales. Thus, fire intensity will vary in space and time as factors that influence fire intensity (e.g. fuel type, fuel load, slope, etc.) vary in space and time (Williams et al. 1994). The dilemma facing researchers has been to quantify these relationships at appropriate spatial scales to achieve a high level of predictability. To this point, our ability to predict fire behavior and fire effects at fine scales has been limited because of a reliance on random sampling of fuel characteristics. We found that these techniques are incapable of detecting spatial variability in fire effects. Ultimately, this leads to increased generalizations and contradictions within the literature. When fuels, fire behavior, and fire effects are related at appropriate spatial scales, the underlying mechanisms that influence variability in fire effects in space and time can be identified.

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Table 1. Differences in weather and fuel conditions for fires conducted in high (n = 14) and low (n = 5) fine fuel moisture conditions.

Variable	High fuel moisture conditions				Low fuel moisture conditions			
	Min	Max	Mean	SE	Min	Max	Mean	SE
Temperature (°C)	28.5	38.5	35.3^{ns}	0.8	33.5	38.4	36.2^{ns}	1.0
Relative humidity (%)	12.4	29.1	19.18*	1.4	22.9	26.1	24.4*	0.6
Wind speed (km hr^{-1})	3.2	11.6	6.2*	0.7	1.0	3.1	1.9*	0.4
Fuel moisture (%)	12.7	29.3	21.2**	1.1	3.0	8.5	4.5**	1.0

Note: *, ** indicate significant differences of means within rows (P < 0.01, 0.0001); ns indicates non-significance.

Table 2. Description of how fuel loads were related to juniper using random and multiscale sampling techniques. Fuel loads were mapped at 0.5 m intervals along a 50 m transect. Fuel loads were related to juniper canopy scorch at various resolutions by averaging 0.5 m plots at random or at the specified spatial scale.

Sampling technique	Resolution (m)	Number of 0.5 m plots	Scale dependence between fuel load and juniper canopy
Random	50.0	10	None; samples collected at random.
Arbitrary scales	1.0	2	Samples summed at the canopy midpoint.
	5.0	10	Samples summed in equidistant directions from canopy midpoint.
	10.0	20	Samples summed in equidistant directions from canopy midpoint.
Canopy scale	1.5 – 6.0	Varies	Samples summed at canopy intercept and vary with canopy size.

Table 3. Variation (adjusted R^2) in juniper scorch characteristics explained by the fuel load that was measured for each sampling technique for two classes of fine fuel moisture (FFM).

Sampling technique	Spatial scale (m)	High FFM (21%)		Low FFM (4%)	
		Scorch height	Scorch volume	Scorch height	Scorch volume
Arbitrary scale	1.0	0.447 ns	0.719*	0.063 ns	0.070 ns
	5.0	0.818*	0.752*	0.225 ns	0.145 ns
	10.0	0.570 ns	0.594 ns	0.273 ns	0.132 ns
Canopy scale	1.5 – 6.0	0.876**	0.789*	0.154 ns	0.096 ns

* $P < 0.05$, ** $P < 0.01$, after Bonferroni correction (Rice 1989); 'ns' indicates relationships that are not significant.

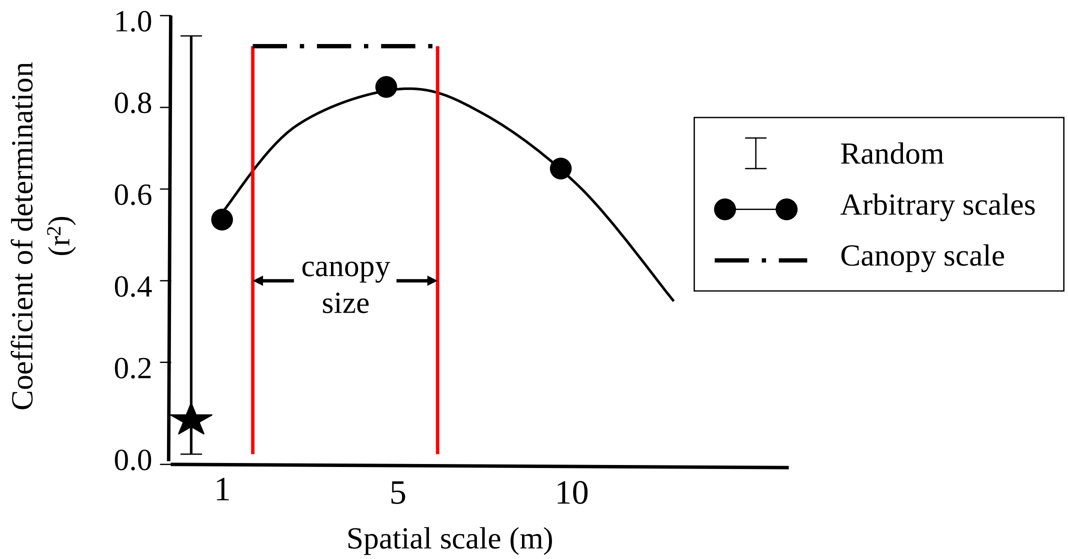
Table 4. Monte Carlo simulation results of the relationship between juniper scorch characteristics and randomly measured fuel loads. Probabilities are the frequency that the correlations (*R*) for random fuel load samples were greater than the correlation (*R*) for fuel loads sampled at the canopy intercept.

Fuel moisture (%)	Scorch characteristic	Mean $R_r \pm 1$ SE	Probability $R_r > R_c$
21	Height	0.162 ± 0.005	0.001
	Volume	0.168 ± 0.005	0.001
4	Height	0.104 ± 0.003	0.02
	Volume	0.098 ± 0.003	0.06

Notes: Abbreviations are as follows: FFM, fine fuel moisture; R_r, Pearson correlation coefficient for fuel load samples collected at random; SE, standard error; R_c, Pearson correlation coefficient for fuel load at the canopy scale. $R_c = 0.936$ and 0.888 for scorch height and volume, respectively, for fine fuel moisture (FFM) = 21%, and 0.392 and 0.310 for scorch height and volume, respectively, for FFM = 4%.

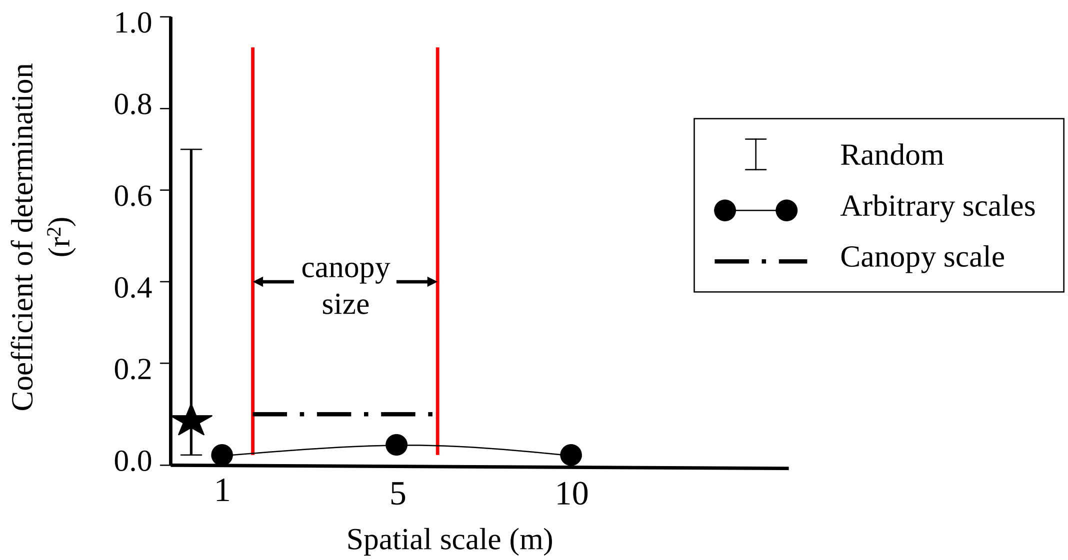
Figure 1. Amount of variation explained by fuel load sampled at random, at arbitrary scales, and at the canopy scale for fires conducted in (a) high fine fuel moisture (21%) and (b) low fine fuel moisture (4%).

(a)



Coefficient of determination (r²)
1.0
0.8
0.6
0.4
0.2
0.0
canopy size
1
5
10
Spatial scale (m)
Random
Arbitrary scales
Canopy scale

(b)



Coefficient of determination (r²)
1.0
0.8
0.6
0.4
0.2
0.0
canopy size
1
5
10
Spatial scale (m)
Random
Arbitrary scales
Canopy scale

CHAPTER II

PROBABILISTIC THRESHOLDS AND THE POTENTIAL REVERSIBILITY OF JUNIPER WOODLAND COMMUNITIES USING EXTREME FIRE

ABSTRACT

Grassland and savanna restoration is a major focus of natural resource professionals in regions that have undergone extensive woody plant encroachment. Fire maintained grasslands and savannas prior to woody plant invasion, but once woody plants dominate, an ecologically irreversible threshold may be crossed. Juniper woodlands are classic examples of post-grassland stable communities that are potentially irreversible with fire. Previous work has identified three mechanistic models that support juniper woodland irreversibility: (1) juniper trees larger than 1.8 m tall are largely uncontrollable with fire, (2) juniper mortality is constrained by fine fuel load, and (3) 30 - 40% canopy cover of juniper limits the amount of area that burns. We tested the validity of these models for summer fires conducted in conditions beyond traditional prescriptions. First, we found fire-induced mortality of juniper was not a function of tree height in these conditions. Second, variation in fine fuel load strongly predicted fire effects on juniper ($r^2 = 0.897$, $P < 0.05$). This supports the feedback mechanism between fuel load and juniper mortality. However, this relationship was only observed when fires were conducted in high fine fuel moisture conditions (21%). Nearly all juniper trees were completely scorched, regardless of fine fuel load, when fine fuel moisture content was low (4%). Third, the relationship between juniper canopy cover and area burned was dependent on the scale of analysis. Our results demonstrate each model is representative of a threshold that occurs within a specific range of environmental conditions. We use these data to outline a probabilistic-based model of thresholds that emphasizes ecological and sociological interactions for use in future restoration objectives (e.g. grassland fire prescriptions) and model development (e.g. state-and-transition models).

Key words: *crown scorch; feedback switch; fire intensity; fire threshold; juniper; probabilistic threshold; resilience; stability; threshold.*

INTRODUCTION

The use of thresholds to describe changes in community dynamics plays a pivotal role in the study of ecological systems. Thresholds are used most commonly to illustrate changes in community dynamics, or more specifically, a change from one stable community to an alternate stable community. Grassland conversion to woodland is an often cited example. Grassland and savanna declines over the past couple centuries have been documented globally (Archer et al. 1995, Brown and Carter 1998) and in North America (Johnsen 1962, Archer 1994). These declines are attributed largely to the encroachment of woody plants resulting, in part, from fire suppression (Bragg and Hulbert 1976). If fires are excluded for long enough time periods, woody plants can dominate, and reintroduction of fire is largely unsuccessful in restoring a grassland dominated community (Archer 1989, Walker et al.

1981, Briggs et al. 2005). The inability of fire to successfully restore dynamics inherent in grassland effectively establishes the occurrence of a fire threshold between these states.

Developing ways to characterize ecological thresholds experimentally is becoming increasingly important. The threshold concept drives state-and-transition models and adaptive management strategies. However, practical use of thresholds in management has been limited because thresholds remain largely conceptual. Although the use of thresholds to distinguish between multiple stable states is generally accepted by the scientific community (Groffman et al. 2006), acceptance of the ecological threshold concept hinges on the fact that thresholds are yet to be validated empirically.

One way of testing threshold dynamics experimentally is to characterize the resilience mechanisms that occur within a given community. Stability and resilience mechanisms maintain community dynamics by resisting feedbacks that may cause the system to cross a threshold to an alternate stable state (multiple stable state concept). The degree with which a state resists change is indicative of the resilience of that state. The juniper woodlands of North America provide excellent examples of how resilience mechanisms can be used to characterize ecological thresholds. In grasslands, the removal of fire from these systems allowed uninhibited juniper encroachment. Once juniper became dominant, a new set of stability and resilience mechanisms ensued, making these communities highly resilient to fire. Thus, characterizing the occurrence of stability and resilience mechanisms that exhibit threshold properties across a broad spectrum of ecological conditions should provide a more detailed understanding of what is needed to cross thresholds between these states.

Juniper woodlands are ideal communities to test fire thresholds because the mechanisms that make these systems resilient to fire are believed to be well known. An increase in the size and distribution of juniper limits fire effects by reducing fine fuel loads, and consequently, fire intensity (Bryant et al. 1983, Engle et al. 1987). Inadequate fine fuel load has been identified as part of the mechanism that is directly responsible for juniper invasion in grasslands (Fuhlendorf et al. 1996, Hoch et al. 2002, Briggs et al. 2005). This helps to explain numerous research that has shown fire-induced mortality of juniper is negatively related to tree height (Martin and Crosby 1955, Dalrymple 1969, Buehring et al. 1971, Owensby 1973, Ortmann et al. 1988, Engle et al. 1988, Engle and Stritzke 1995). These resilience mechanisms make juniper woodlands highly stable post-grassland communities (Archer 1989, Walker et al. 1981, Briggs et al. 2005, Briske et al. 2006) and potentially implicate the occurrence of a fire-juniper threshold that may be irreversible (Fuhlendorf et al. 1996, Hoch et al. 2002).

If thresholds do in fact exist, then we should be able to characterize their occurrence by identifying and testing various mechanisms of resilience that underpin threshold dynamics. We know of no study to date that has rigorously tested or validated the threshold concept through experimentation. We use juniper woodlands to test the occurrence of thresholds because mechanisms of resilience in these systems are well-known. We use these well-known mechanisms to construct three models that support the occurrence of a fire-juniper threshold (Figure 1). First, we test the model that juniper mortality decreases with tree height and is limited to trees less that 1.8 m in height. Second, we test the model that mortality of juniper is dependent on abundant fine fuel loads. Finally, we test a third model that states fire is incapable of spreading in grasslands that consist of greater than 40% juniper canopy cover. These models were used to test the threshold concept because (1) high levels of mortality have not been documented at taller heights (Table 1), (2) fine fuel load is specifically identified as a prerequisite for juniper control (Fuhlendorf et al. 1996, Hoch et al. 2002, Briggs et al. 2005), (3) juniper canopy cover of 40% is used to indicate when fire can no longer be conducted successfully in juniper dominated grasslands (USDA, NRCS 2004), (4) these models are applied currently in numerous state-and-transition models to indicate the occurrence of a threshold that separates grassland/savanna and juniper woodland stable states (USDA, NRCS 2004), and (5) no study has shown that prescribed fire can successfully overcome these thresholds in mature juniper woodlands. Even frequent fires have failed to decrease juniper woodland dominance (Hoch et al. 2002, Briggs et al. 2005). It has often been suggested that fires conducted in more extreme conditions could increase woody plant mortality (Bruner and Klebenow 1979, Bryant et al. 1983, Fuhlendorf et al. 1996, Briggs et al. 2005). However, data are limited since most fire practitioners are unwilling to burn in these conditions.

The purpose of this study is to test the occurrence of fire thresholds within juniper woodland communities. We hypothesize that each threshold model (Figure 1) is dependent on a restrictive set of environmental conditions that constrain fire intensity. We tested this hypothesis by conducting growing season burns in conditions that were outside the range of traditional prescriptions. We use these data to increase our understanding of threshold dynamics, determine potential mechanisms of reversibility in juniper woodlands, and facilitate the integration between ecological threshold dynamics and the socially derived objectives that drive resource management.

METHODS

Study Area

This study was conducted at the Sonora Texas Agriculture Experiment Station located on the Edward's Plateau. Mean annual precipitation on the site averages 600 mm but has varied from 156 mm to 1054 mm, resulting in episodic droughts during the summer (Station Records 1918 to 2005). Soils on the area are typically shallow with frequent rock outcrops (Wiedenfeld and McAndrew 1968, Fuhlendorf and Smeins 1996). This, coupled with the continued invasion of *Juniperus* spp. at the site, disrupts fine fuel continuity and reduces fine fuel loads.

Historically, this area was a relatively open grassland and savanna matrix interspersed by clusters of *Quercus* spp. Juniper canopy cover was less than 1% at the Sonora Station (Smeins et al. 1997) in 1948; however, alteration and removal of fire has enabled woody plants to invade and dominate this area. Now the site is characterized as oak/juniper woodland. At present, juniper canopy cover alone exceeds 20% (Smeins et al. 1997), while the total canopy cover of woody plants exceed 40%.

The grassland/savanna progression to a juniper woodland that has occurred at the Sonora Station is consistent with invasion patterns outlined in state-and-transition models of Low Stony Hill ecological sites (USDA, NRCS 2004). The historic grassland community transitioned between a midgrass/oak savanna to a midgrass oak/shrub savanna through an interaction between fire and grazing. The historic midgrass/oak savanna consisted of less than 5% total woody cover. As time since fire increases, the oak savanna state transitions to a midgrass oak/shrub savanna with higher levels of woody canopy cover (10 – 25%). It is for this state or condition that USDA-NRCS indicates that juniper can be controlled up to a height of 1.5 m (USDA, NRCS 2004). If fires are not conducted before trees grow to this height, the state progresses to an oak/juniper woodland (40% total canopy cover) at which point fire is largely ineffective (Wink and Wright 1973, Engle and Stritzke 1995).

Experimental design

Nineteen 50 m transects were established at random. Two stakes were used to permanently mark each end of the transect. Transects were oriented in the direction of the prevailing wind so that all fires propagated as headfires. Transects were marked at 1 m intervals to monitor fire spread and to increase precision when resampling transects at a later date.

Fire prescriptions

Nineteen transects were burned during wet (n = 14) and dry (n = 5) periods of the summer. Transects were burned by igniting a 10 m wide headfire at the beginning of each transect. All fires were conducted in conditions that were beyond the range of traditional prescriptions for this region. Fire prescriptions in this region are normally limited to temperature below 27°C, relative humidity above 20%, and wind speed less than 32 km per hour (Wright and Bailey 1983). Weather conditions were well beyond these recommendations for this study. Temperature averaged 35.3° ± 2.7°C and relative humidity (mean = 20.5 ± 5.1%) was frequently lower than 20% (10 of 19 transects). Wind speed was the only variable within the range of traditional prescriptions. Winds were light and variable in this study, averaging 6.1 ± 2.6 km per hour.

Weather conditions were held as constant as possible among all fires, but some small statistical differences were observed (Table 1). Mean relative humidity was 19.1% and 24.4% for wet and dry portions of the summer. These means were significantly different (t = -2.21, $P < 0.05$). Wind speed was light in all fires, but the means differed between fire events (t = 3.67, $p < 0.01$). Temperature was the only variable that did not differ between fires (t = -0.62, p = 0.55).

Fine fuel load and fine fuel moisture were also considered as part of the fire prescription because variation in these characteristics can influence fire intensity over space and time. We specifically targeted two different levels of fine fuel moisture. Fine fuel moisture was 21.2 $\pm$ 4.2% and 4.5 $\pm$ 3.0% during wet and dry periods, respectively (t = 8.31, $p < 0.0001$). This represented the greatest difference among fuel and weather characteristics between years (Table 1). Fuel load was not significantly different between fire events (P = 0.20).

Testing threshold 1:
Juniper height – fire effects threshold

We first tested the model that fire effects on juniper are limited to trees less than 1.5 m tall (Figure 1a). The line-intercept method was used to measure juniper crown cover along the transect. Tree heights were recorded for those junipers with crowns that intersected at least 50 cm of the transect. Tree heights were separated into four classes (0.0 – 0.9 m, 1.0 – 1.9 m, 2.0 – 2.9 m, and > 3.0 m).

Juniper mortality and crown scorch were recorded two to three weeks following the burns. Juniper mortality was defined as 100% scorch of the canopy. Crown scorch was estimated as the proportion of the crown that was scorched (%). A measure of scorch proportion was used as an alternative to the standard measure of scorch height because scorch height (m) is not an appropriate estimate of fire intensity when tree height limits the potential scorch of the crown.

Fire effects on juniper trees were assessed only for juniper trees that occurred within areas that burned along the transect. This decision was made *a priori* because large patches of unburned areas are commonplace in this region and partially burned or unburned transects were expected. Altogether, seventeen trees were located within areas that burned along the transect.

Testing threshold 2:

Fuel load – fire effects threshold

Fine fuel load was quantified every 50 cm along the transect within 50 x 50 cm quadrats. Fine fuel load was estimated visually as one of four fuel load classes in each 50 x 50 cm quadrat because destructive sampling of fuels would alter fire behavior along the transect. Fuel loads classes were calibrated by visually estimating the amount of fuel within a 0.25 m^2 quadrat and comparing it to the actual fuel load by clipping ($n = 50$). Calibration of this technique revealed fuel load classes were significantly different (Table 2) and was a reliable estimate of actual fine fuel loads ($r^2 = 0.90$, $P < 0.0001$).

Fuel load was sampled in this manner to determine the most appropriate scale to relate fuel load to fire effects on juniper. To date, fine fuel load has not been related to fire effects on juniper in a spatially explicit context, instead relying on random sampling techniques. This measure has serious shortcoming in environments with highly heterogeneous fine fuels . Here we only present the results as a function of the mean fuel load that occurred beneath the canopy of juniper trees because fire effects on juniper were best predicted at this location. The mean fuel load that occurred beneath the canopy was obtained by aggregating attributes of individual quadrat samples along the transect that corresponded to the canopy intercept.

Fine fuel moisture was measured in addition to fine fuel load. Fine fuel moisture was reported as the mean fuel moisture of the entire fuel complex (i.e. live and dead fine fuel moisture were not considered independently). Fine fuel moisture was collected by clipping five random 0.25 m^2 quadrats adjacent to each transect (n = 5). Moisture content of the fine fuel was determined on a dry-weight basis.

Testing threshold 3:

Canopy cover – area burned threshold

Juniper canopy cover was related to area burned to test the model that increasing juniper cover decreases fire spread (Figure 1c). Juniper canopy cover was measured using the line-intercept method. Fire spread was monitored during the course of the burn to quantify unburned patches that remained after passage of the fire front. Markers established along the transect prior to the burn were used as guides to ensure that measurements of fire spread were taken along the initial transect trajectory.

To determine whether the relationship between juniper canopy cover and area burned (Figure 1c) was dependent on spatial scale, the amount of area that burned was compared to juniper canopy cover within the transect (at 10 m intervals) and for the entire transect (50 m). For the 10 m scaled analysis, juniper canopy cover and area burned were averaged among the five 10 m segments in each transect, as long as fire propagated within a given segment. In these cases, when the fire stopped within a previous 10 m segment of the transect, the amount of woody canopy cover in the following segment was not considered to influence the amount of area that burned in the previous segment, and thus, was excluded from the analysis.

Statistical analysis

Comparisons were drawn among our data and the predicted relationships in the models (Figure 1) using regression analysis. Regressions were fit with least square regression lines. Regressions that were not significant are shown so that comparisons can be drawn with the predicted relationships in Figure 1. Comparisons between groups were analyzed using t-tests or one-way or two-way ANOVA's.

RESULTS

Threshold 1: juniper height and crown scorch

We first tested the model that fire only controls juniper less than 1.8 m in height (Figure 1a). In this study, mortality occurred across all height classes. About half (42%) of the juniper trees were completely scorched and some of those were among the tallest trees (4.5 m) measured. Only one tree less than 2 m in height was located in burned patches along the transect and was scorched completely. For the following height classes, 2.0 – 2.9 m, 3.0 – 3.9 m, and greater than 4.0 m, percent mortality was 75% (n = 4), 57% (n = 7), and 60% (n = 5), respectively. Differences among height classes were not significant (Table 3).

Juniper mortality was defined as trees with 100% scorch, however, this definition failed to quantify variability in fire effects. An assessment of fire-induced damage to the juniper crown provided a more precise measure of fire effects. We found tree height predicted crown scorch poorly in this study due to increasing variability in crown scorch at increasing tree heights (Figure 2).

Threshold 2: fuel and fire effects

The second model was tested to validate the predicted relationship between fuel load and juniper scorch (Figure 1b). According to the model, at some point fuel load limits the amount of crown scorch caused by the fire. In this study, crown scorch was related directly to fine fuel load when fine fuel moisture was high (Figure 3). However, nearly all trees were scorched completely, regardless of the amount of fine fuel beneath the canopy, when fine fuel moisture was low (Figure 3). Mean crown scorch was 50% greater in these conditions (Table 4).

These data suggest fine fuel load and fine fuel moisture should be treated as variables that interact to influence fire effects and not as main effects variables. A two-way ANOVA was conducted to explore this interaction. The resulting analysis indicated the interaction between fuel load and fuel moisture explained 97.8% of the total variation (R^2) in juniper crown scorch across all fire events ($P < 0.001$) (Table 5).

Threshold 3: canopy cover and area burned

The last model we tested evaluated the relationship between juniper canopy cover and the amount of area burned. Mean juniper canopy cover and total woody cover among transects were 30.3% and 52.1%, respectively. Juniper canopy cover ranged from 0.0 to 73.4% among transects. Four of 19 fires burned the length of the entire transect, while 5 transects did not burn at all. For all other transects (n = 10), fire spread stopped at some point within the transect.

We found the relationship between juniper canopy cover and area burned to be dependent on the scale of analysis. Although the amount of area burned was predicted poorly by juniper canopy cover along the entire transect ($R = 0.509$), the perimeter of the data is along the same trajectory as the predicted model (Figure 4 vs. Figure 1c). However, an obvious trend between area burned and juniper canopy cover was not apparent when analyzed at 10 m intervals within transects (Figure 4b).

DISCUSSION

Fire in juniper woodland

We tested the validity of three threshold models that suggest grassland can not be restored following conversion to juniper woodland (Figure 1). Each threshold model was constructed to emulate current hypotheses that direct rangeland science and management within juniper woodlands. Specifically, these models test the following hypotheses: juniper mortality is reduced when trees exceed 1.8 m in height (Figure 1a); juniper crown scorch and mortality are dependent on abundant fine fuel load (Figure 1b); juniper canopy cover between 30 – 40% prohibits fire spread and limits the amount of area burned (Figure 1c). We found these models do not accurately portray fire dynamics (i.e. fire effects and burned area) when fires are conducted in a variety of environmental conditions. We propose these models are only valid when practitioners limit fire intensity to a narrow range of fuel and weather conditions.

Our results do not support the occurrence of a juniper height – fire effects threshold when fires are conducted in extreme conditions. The model predicted fire effects on juniper would be difficult to attain at heights greater than 1.8 m (Figure 1a). A similar trend was observed in this study when fires were conducted in high fuel moistures (21%) but we found no evidence to suggest fire effects on juniper decrease with tree height among all fire and fuel moisture events (Table 4, Figure 2). Even some of the tallest trees (4.5 m) were scorched completely and variability in crown scorch increased with tree height in this study (Figure 2). These results demonstrate the juniper height – crown scorch model is not an accurate predictor of fire effects on juniper across all fire events, thereby implicating other mechanisms are driving juniper crown scorch.

In exploring possible explanations for the application of the juniper height – fire effects threshold (see USDA, NRCS 2004), we came across numerous studies that support the model depicted in Figure 1a. A height of 1.8 m was designated as the inflection point to test the juniper height – fire effects threshold since mortality decreased rapidly for taller trees (Wink and Wright 1973). Similar inflection points are applied currently in numerous regions to indicate the point at which grassland/savanna transitions to juniper woodland (Engle and Stritzke 1995, USDA, NRCS 2004). Not only do our results differ markedly from previous findings, but upon further review of the studies that contributed to the application of this threshold, the universal acceptance of this model is not warranted necessarily. Fire effects on juniper were highly variable among the studies that support the application of this threshold (Table 6). We contend the juniper height – fire effects threshold is an oversimplification of the actual relationship and emerged only by ignoring the considerable variability in fire effects within and among the initial research (Table 6, Figure 5).

The second threshold (Figure 1b) is applied within rangelands to illustrate a critical amount of fine fuel must be available to increase fire intensity to a point that can cause mortality on mature juniper trees. Unfortunately, application of this model is limited as it only describes a fraction of the potential pathways that could lead to high juniper mortality. Clearly the threshold depicted in the model exists (Figure 1b). High fine fuel loads indeed achieved high levels of mortality in this study when fine fuel moisture was high (Figure 3); however, the threshold exists only when all other variables that influence fire intensity are not contributing much to the overall intensity of the fire. Fire effects in this study were not only dependent on fine fuel load but on the interaction between fine fuel load and fine fuel moisture (Table 5). When fires were conducted in low fine fuel moistures, the relative importance of fine fuel load changed considerably (Figure 3). Future analyses need to recognize fire effects are dependent on any combination of factors that influence fire intensity if fire effects are to be predicted with greater accuracy. The sole use of main effects for analyses may lead to unreliable results in many situations when they are interacting with other variables (e.g. fuel moisture) that influence fire intensity as well. Further combinations of these interactions need to be explored to develop a model that does not rely solely on fine fuel load.

The third threshold tested in this study (Figure 1c) was dependent on the scale of the analysis. The third threshold model typified the relationship between juniper canopy cover and area burned. We found the threshold in the model was mimicked when juniper canopy cover and area burned were related at the scale of the 50 m transect. Although the variables were correlated weakly ($R = 0.509$), distribution of the data typified the trend shown in the tested model (Figure 4a vs. Figure 1c). The relationship between juniper canopy cover and area burned was weakly related because area burned was highly variable when juniper canopy cover was 20% or less. This variable trend was exacerbated when analyzed at the scale of the 10 m segment within the transect. At this scale, area burned was highly variable for all values of juniper canopy cover (Figure 4b). Thus, the juniper cover – area burned threshold appears to be scale dependent. Further research needs to be conducted to determine the mechanisms that drive variability in the amount of area burned across various spatial scales within juniper woodland to solve these discrepancies.

We propose further investigations focus on intensity as the component of the fire needed to cause sufficient mortality within juniper woodland and thereby allowing potential reversal of the juniper – fire threshold. Previous works have identified different pathways that may trigger threshold reversal. These pathways included frequent fire (Hoch et al. 2002, Heisler et al. 2004, Briggs et al. 2005) and/or high fine fuel loads (Buehring et al. 1971), but limited data were available to confirm or negate these hypotheses. Many studies have shown woody plants, including juniper, are not reduced by frequent fires (Heisler et al. 2004, Briggs et al. 2005). Indeed, frequent fires are likely to have little impact on woody plants if fires are of insufficient intensity. Quantifying the intensity needed to reduce woody plants, and how often fires of this intensity are applied, may be the key to understanding mechanisms of threshold reversal in the future.

Refinement of threshold concept

The lack of validation of the threshold models tested in this study does not mean fire-juniper thresholds do not exist, but rather their occurrences are exaggerated. Our findings lead us to adopt a probabilistic interpretation of thresholds that expands upon a recently proposed framework for threshold assessment and application (Briske et al. 2006). A probabilistic framework identifies thresholds as being constrained to a specific set of environmental conditions that govern their probability of occurrence. In other words, probabilistic thresholds occur only as long as specific conditions persist to stabilize the threshold. These conditions are yet to be quantified for many, if not all, ecological thresholds. Here we use our findings to illustrate potential gains that may be obtained from incorporating a probabilistic framework into the assessment and application of ecological thresholds.

In this study we have identified three parameters that reinforce the probabilistic threshold concept. First, thresholds may be scale dependent (e.g. juniper cover-area burned threshold). This should be fairly intuitive since descriptions of ecological thresholds are based on pattern-process relationships. Most, if not all, pattern and process relationships exhibit some sort of scale dependency. If the pattern-process dynamics that define thresholds are scale dependent, then the thresholds themselves must be scale dependent.

Second, thresholds may be dependent on interactions among multiple environmental variables (e.g. fuel load-fire effects threshold). Ignoring these interactions lead to generalization of the data and oversimplification of threshold dynamics. At a minimum this reduces our ability to quantify the conditions that characterize probabilistic thresholds. Even worse, we may fail to recognize probabilistic properties of thresholds altogether. As a consequence, thresholds are rarely applicable in models and restoration tasks because the underlying mechanisms that govern threshold dynamics are poorly understood. The relationship between fuel load and fire effects in juniper woodland communities epitomizes this consequence. High mortality within mature juniper woodland is indeed difficult if fuel load is the only mechanism driving mortality, especially considering that reduction of fine fuel loads is an inherent result of juniper invasion into grassland. Identifying the interaction between fine fuel moisture and fine fuel load increases the number of pathways available to a resource professional whose aim is to surpass the juniper-fire threshold and restore pre-threshold grassland dynamics.

Third, identification of a threshold may be an artifact of environmental constraints imposed by anthropogenic interests. In these cases, the conditions needed to destabilize the threshold can be obtained if the anthropogenic influence is altered or removed. For example, the model that portrays juniper height to be negatively related to scorch/mortality is an artifact of most prescribed burns being conducted within a narrow window of environmental conditions. Prescribed fires are normally conducted during conditions that limit fire intensity so that safety and containment is ensured. A cautionary approach to prescribed fire may meet this objective but it prevents the maximum potential fire effects from being obtained. As a result of targeting extremely low fine fuel moisture conditions with the intent of maximizing fire intensity, we observed crown scorch at higher levels than had been reported previously (Table 3 versus Table 5) (Engle et al. 1988, Engle and Stritzke 1995). Thus, previous studies found tree height to be a limitation to juniper mortality only because fires were conducted in conditions that were incapable of producing sufficient fire intensity to cause complete scorch across all height classes (Bunting 1983, Bryant et al. 1983, Engle et al. 1987, Engle and Stritzke 1991, Engle and Stritzke 1995). Here we have not only identified this ecological threshold as being probabilistic, but the probability that this threshold occurs is reinforced further by social thresholds that prevent extreme prescribed fire and maximum fire effects.

The ability to reverse the grassland to woodland threshold may hinge on managerial and social acceptance of ecologically derived probabilistic thresholds. As we have shown, fire can be successful in triggering high levels of juniper mortality in the post-grassland threshold state if conditions permit sufficient fire intensity. However, current policy does not allow managers to burn in these conditions since they are beyond traditional recommendations (Wright and Bailey 1982). This managerial constraint effectively establishes a social threshold. Although the threshold may be reversed ecologically, the unwillingness, or inability, of managers to conduct prescribed fires in these conditions precludes threshold reversal.

Natural resource professionals need to evaluate the interface between social and ecological thresholds for model development (e.g. state-and-transition models) and restoration objectives (Provenza 1991). As probabilistic thresholds are identified across multiple spatial and temporal scales, the potential for threshold reversal in restoration management will become more apparent. These probabilities can then be used in models that are founded on threshold occurrence (e.g. state-and-transition models) and the risks and benefits associated with the conditions required to trigger threshold reversal can be assessed by resource specialists. Still, unless current policies change so that burns can be conducted in ‘more extreme’ conditions, social thresholds will continue to cause fire to be largely unsuccessful in reversing woodland-infested grasslands.

CONCLUSIONS

Many thresholds that have been identified previously are probabilistic and their occurrence is limited to a specific range of environmental conditions. Social and ecological inputs determine the probabilities associated with components of thresholds, and thus, the magnitude of threshold reversibility (i.e. resilience) of the post-threshold community. In this study, we found that previously identified mechanisms that were hypothesized to prevent threshold reversal can be reversed when social factors (e.g. fire policy) do not limit the potential range of ecological conditions that influence fire intensity. Natural resource professionals may not be ready to conduct prescribed fires in these conditions, but we have shown a way to trigger feedbacks that can potentially reverse the grassland-woodland threshold. As probabilistic thresholds are quantified in further detail, perhaps the probabilities associated with social thresholds will change to accommodate restoration requirements.

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Table 5. Historical representation of the relationship between tree height and juniper control and mortality. A height of 1.8 m was designated as juniper-fire threshold inflection point due to the general consensus that mortality was inversely related to tree height. This specific value was likely based on results from Wink and Wright (1973) since no other study has documented complete mortality of juniper above that height.

Reference	Tree size (m)	% control*	% mortality
Dalrymple 1969	< 0.6		100
	0.6 – 1.8		77
	> 1.8		27
Buehring et al. 1971**	< 0.45	100 (Site 1)	100 (Site 1)
		92 (Site 2)	98 (Site 2)
	0.45 – 0.9	90 (Site 1)	90 (Site 1)
		75 (Site 2)	85 (Site 2)
	0.9 – 1.8	70 (Site 1)	60 (Site 1)
		55 (Site 2)	70 (Site 2)
Owensby et al. 1973	< 0.6	89	72
	0.6 – 1.8	83	48
	> 1.8	39	20
Ortmann et al. 1998	< 1.0		88
	1.0 – 2.0		60
	2.0 – 3.0		35
	> 3.0		10
Wink and Wright 1973	< 1.8		99

*% control is defined as the percentage of trees that exhibit obvious effects from treatment (e.g. scorch, dead branches) (definition adapted from Owensby et al 1973).

**values are approximated from a figure in the publication; percent control represents trees exhibiting scorch within one month of each burn; percent mortality represents effects one year after burn.

Table 6. Mean (± SE) fuel and weather conditions for fires that were conducted during a wet and dry period of the summer.

Variable	Wet-period fires (n = 14) (mean ± SE)	Dry-period fires (n = 5) (mean ± SE)	*P*
Temperature (˚C)	35.27 ± 0.77	36.15 ± 0.97	0.50
Relative humidity (%)	19.07 ± 1.41	24.44 ± 0.59	< 0.01
Wind speed (km hr^{-1})	6.21 ± 0.68	1.87 ± 0.35	< 0.01
Fuel load (g m^{-2})	209.8 ± 48.1	293.1 ± 37.6	0.20
Fine fuel moisture (%)	21.16 ± 1.13	4.48 ± 1.03	< 0.0001

Table 7. Calibration of fuel load classes obtained by visually estimating the amount of fuel within 50 randomly selected 0.25 m^2 quadrats and comparing those estimates to the actual fuel load that was clipped from each quadrat.

Fuel load class	*n*	Fuel load ($g\ m^{-2}$) (Mean ± SE)
0	9	$10.67^{a} \pm 1.17$
1	17	$97.75^{b} \pm 3.55$
2	13	$220.31^{c} \pm 5.34$
3	11	$406.18^{d} \pm 10.16$
P		< 0.001

Note: Comparisons of fuel load class means with one-way ANOVA. Within columns, numerical values followed by different letters are significantly different ($P < 0.001$).

Table 8. Mean (± SE) scorch and mortality for three height classes of juniper.

	Height classes (m)			
Variable	2.0 – 2.9	3.0 – 3.9	≥ 4.0	*P*
Crown scorch	73.8 ± 17.7	70.7 ± 16.6	77.0 ± 19.2	0.97
Tree mortality	75 ± 28.9	57 ± 18.4	60 ± 20.0	0.71

Note: no significant differences ($P > 0.05$) were observed for comparisons between groups within rows.

Table 9. Mean (± SE) scorch and number (n) of juniper trees that were burned for fires conducted in fine fuel moistures of 21% and 4%.

Fine fuel moisture (%)	*N*	Scorch height
21	7	51.66 ± 17.10[a]
4	10	99.43 ± 0.57[b]

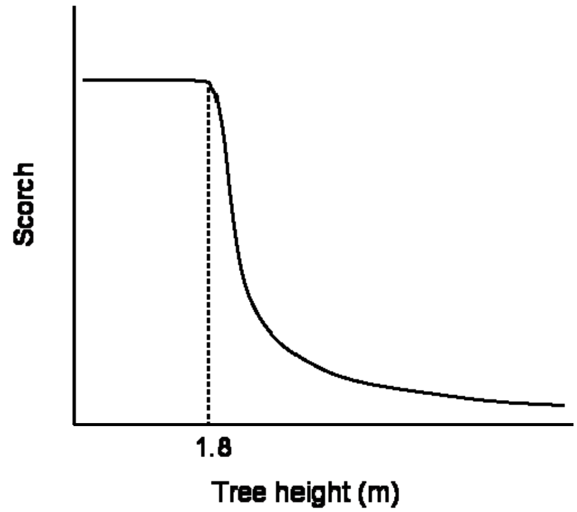
Note: Within columns, numerical values followed by different letters are significantly different ($P < 0.05$).

Table 10. Two-way ANOVA for juniper scorch vs. fuel load and fuel moisture for 19 fires conducted in the growing season. Model explains 97.8% of the total variation (R^2) in juniper scorch ($P < 0.001$).

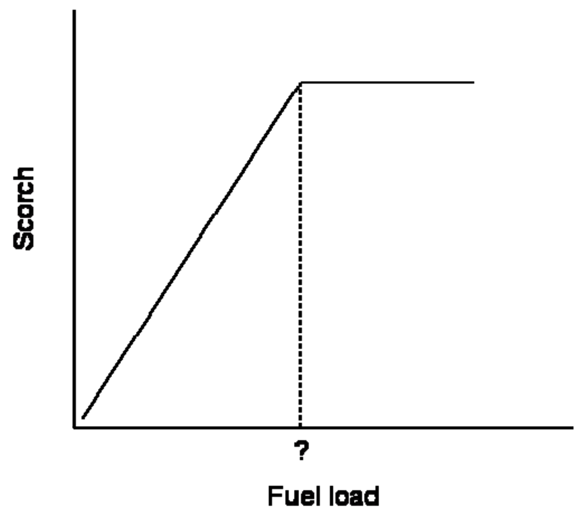
Dependent variable	df	*F*	*P*
Model terms			
Fuel load	2	35.98	< 0.001
Fuel moisture	1	66.17	< 0.001
Load x moisture	2	25.05	< 0.01
Error	6		

Figure 2. Models of the juniper woodland thresholds tested in this study. All models are currently applied in grasslands and savannas that are experiencing juniper encroachment to illustrate that the fire-juniper threshold is potentially irreversible. Figure A typifies the association between tree height and the effect of fire on juniper. Figure B signifies the relationship between fuel load and juniper scorch. Figure C illustrates the relationship between juniper canopy cover and fire spread. These trends represent the mechanisms that support the more overarching theory regarding grassland and savanna maintenance and restoration. As long as abundant fine fuel loads exist and juniper has not reached the indicated level of dominance, the system can be maintained and/or restored; however, once juniper achieves dominance, fire is considered to be incapable of restoring the pre-threshold grassland or savanna community.

(a)


Scorch
1.8
Tree height (m)

(b)


Scorch
?
Fuel load

(c)

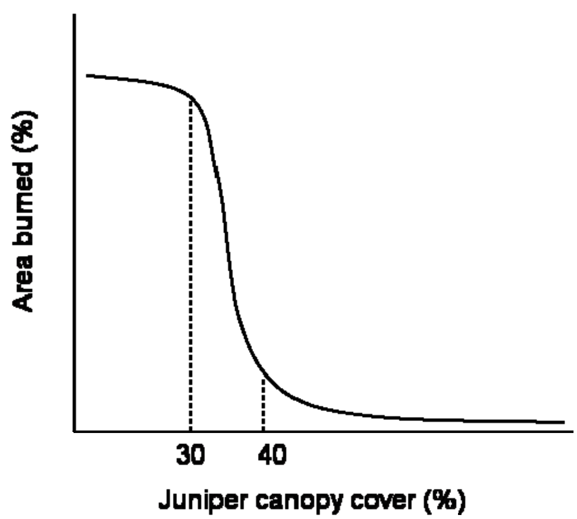

Area bumed (%)
30
40
Juniper canopy cover (%)

Figure 3. Relationship between tree height and crown scorch of juniper. The diagram inlaid in the main figure demonstrates the inverse relationship between juniper height and fire effects. Height classes were used to analyze the relationship in a manner similar to historical accounts so that it could be compared to the applied model. Each column in the smaller diagram represents a juniper height class of 1.0 – 1.9 m, 2.0 – 2.9 m, 3.0 – 3.9 m, and > 4.0 m, respectively. Although a negative relationship generally exists between tree height and crown scorch, the relationship was highly variable in this study (main figure).

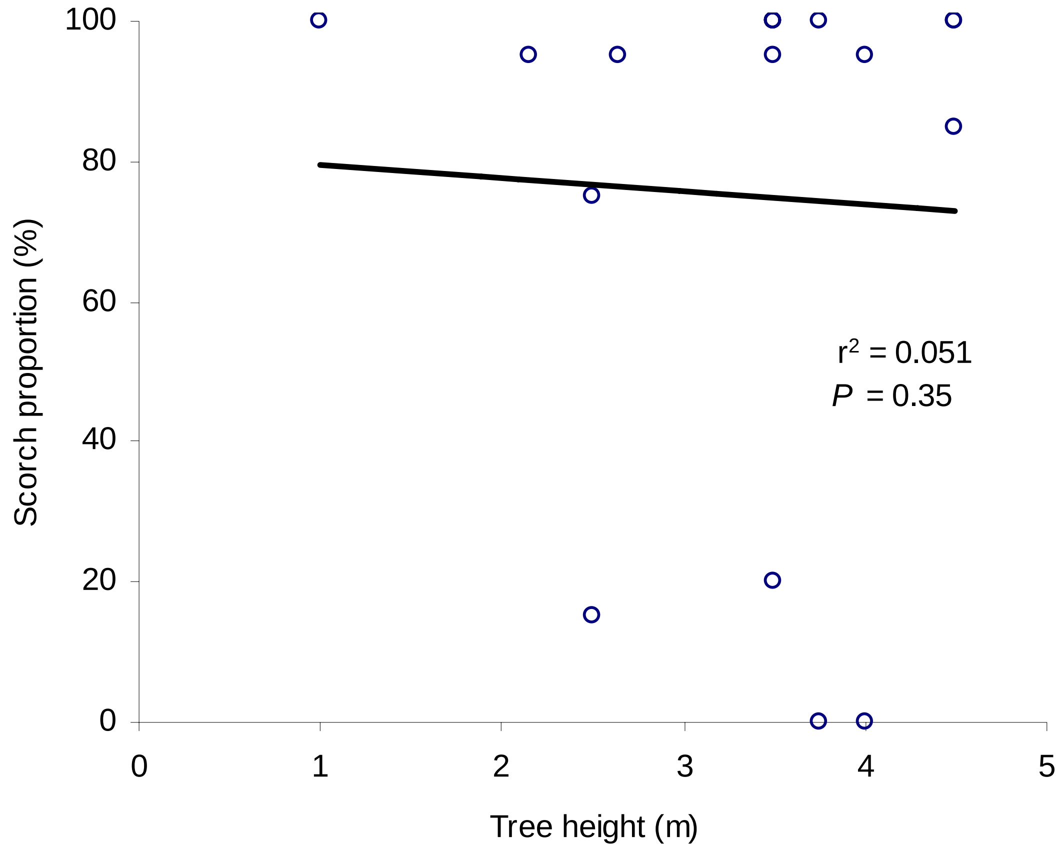

100
80
60
40
20
0
0
1
2
3
4
5
Scorch proportion (%)
Tree height (m)
r2 = 0.051
P = 0.35

Figure 4. Relationships between the mean fuel load under the canopy and crown scorch for fires conducted in high (circles) and low (diamonds) fine fuel moisture events.

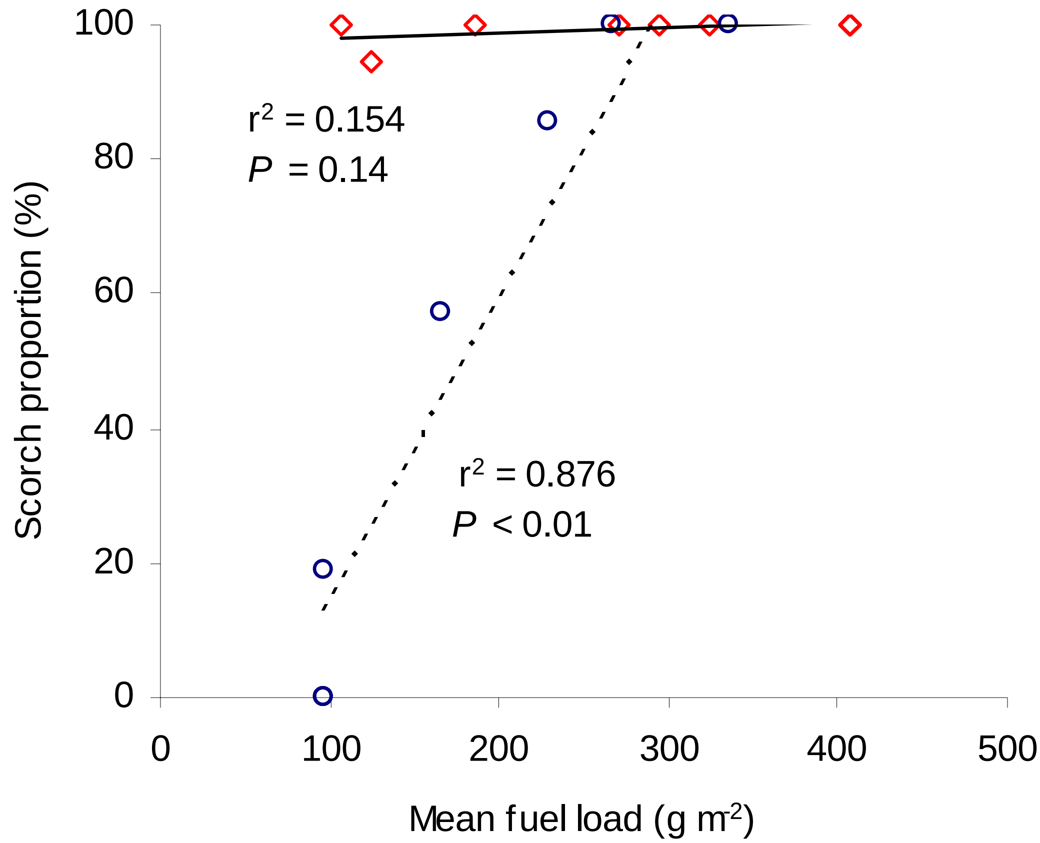
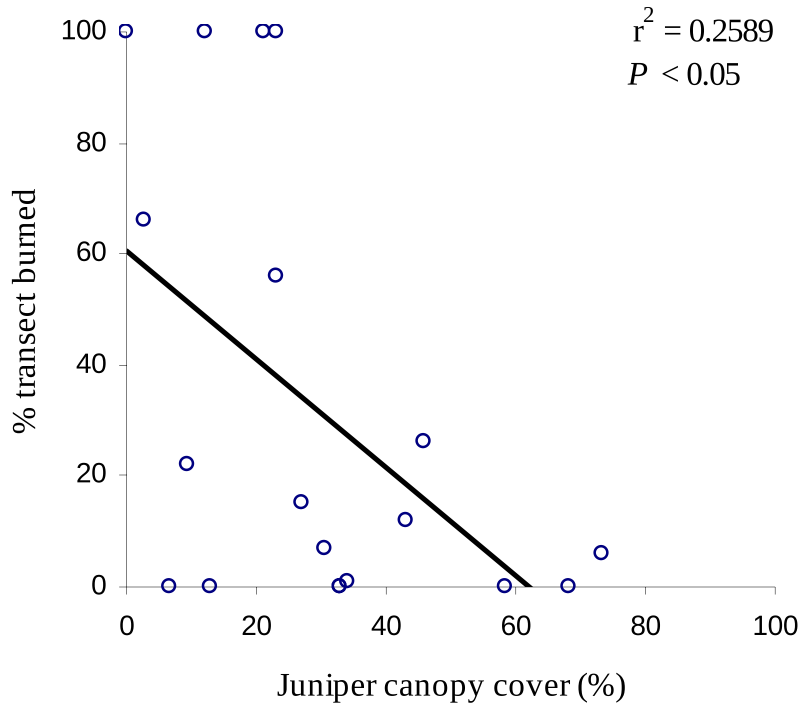

100
80
60
40
20
0
0
100
200
300
400
500
Scorch proportion (%)
Mean fuel load (g m-2)
r2 = 0.154
P = 0.14
r2 = 0.876
P < 0.01

Figure 5. Relationship between fire spread and juniper canopy cover at scales of (A) the 50 m transect and (B) 10 m segments of the transect.

(a)


% transect burned
Juniper canopy cover (%)
r2 = 0.2589
P < 0.05
0
20
40
60
80
100

(b)

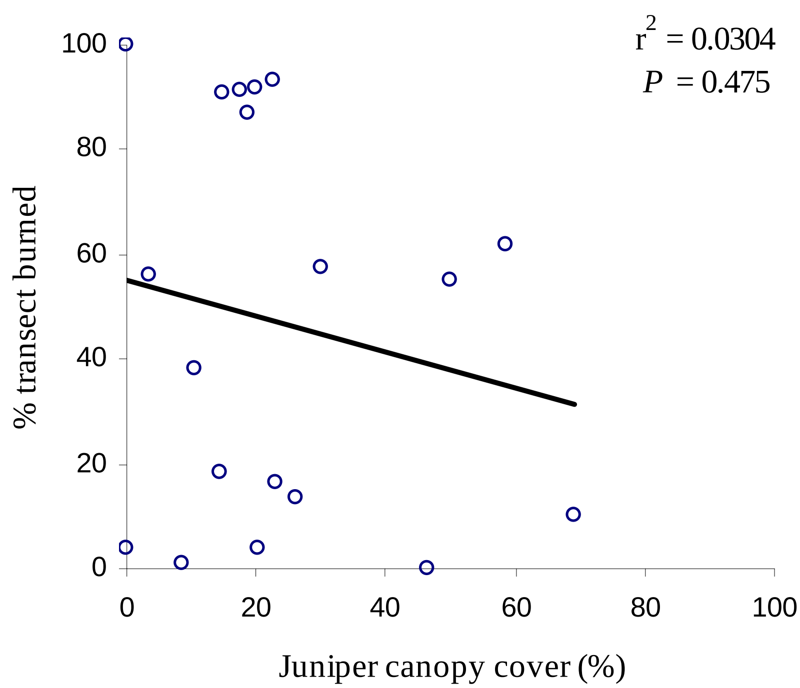
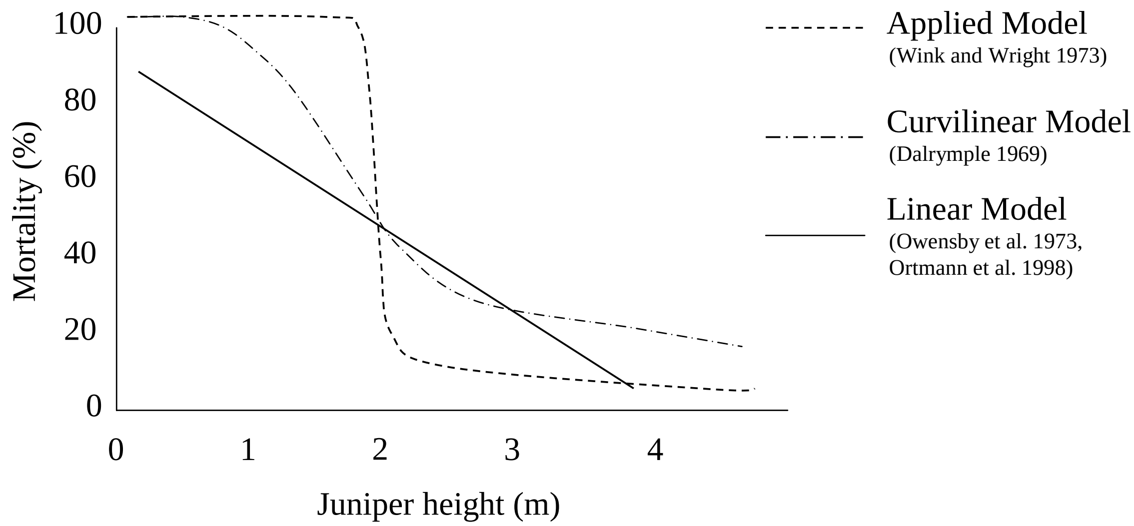

% transect burned
Juniper canopy cover (%)
r2 = 0.0304
P = 0.475
0
20
40
60
80
100

Figure 6. Projected relationships between mortality and tree height that were derived from the findings of various historical references (data presented in Table 5). The applied model supports the overarching theory that fire is incapable of triggering threshold reversal in juniper woodlands. However, projecting data from numerous works hardly supports the universal application of this threshold. Projections suggest multiple models exist. Previous works collectively agree that fire-induced mortality is negatively related to juniper height. When combined with results from this study, the juniper height-mortality threshold only occurs within a specific range of environmental conditions.


100
80
60
40
20
0
Mortality (%)
0
1
2
3
4
Juniper height (m)
Applied Model
(Wink and Wright 1973)
Curvilinear Model
(Dalrymple 1969)
Linear Model
(Owensby et al. 1973,
Ortmann et al. 1998)

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Major Field: Rangeland Ecology and Management

Scope and Method of Study: The reintroduction of fire into grassland and savanna systems invaded by *Juniperus* has been unsuccessful largely in restoring grassland or savanna community dynamics. Here I focus on the use of extreme fire as a potential tool in the restoration of a *Quercus* savanna invaded heavily by *Juniperus*.

Findings and Conclusions: I found extreme fire can induce high levels of mortality in mature *Juniperus* woodland. However, multiple pathways can produce the fire intensity necessary to create these effects. The successful use of extreme fire in this study demonstrates that prior restoration attempts were futile because the fire thresholds believed to preclude restoration of *Juniperus* woodland are contingent upon (1) scale dependencies in relating fuels, fire behavior, and fire effects, (2) an inability to identify interactions among multiple environmental variables, and (3) social constraints that prevent the occurrence of specific processes that drive ecological restoration.

ADVISER'S APPROVAL: Sam Fuhlendorf