

Surface Fuel Sampling Strategies: Linking Fuel Measurements and Fire Effects

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Abstract

We assessed the effectiveness of different sampling strategies in linking fine fuel load and crown scorch of ashe (*Juniperus ashei*) and redberry juniper (*J. pinchotii*) for prescribed fires conducted in wet and dry periods of the growing season on the Edwards Plateau, Texas, USA. Our aim was to determine if spatial and temporal variation in crown scorch was best predicted by estimates of fuel load sampled with spatially explicit, multiscale sampling strategies or with traditional, simple random sampling of fuel load. We found that multiscale sampling of fuel load underneath and adjacent to juniper crowns was more effective than simple random sampling in predicting crown scorch for the 14 fires conducted in the wet period and the five conducted in the dry period. The type of sampling strategy employed was critical in relating fuel load to crown scorch during the wet period. Percent crown volume scorched ranged from 0% to 100% in these conditions. In contrast, the type of sampling strategy was less important in the dry period when crown scorch was >90% for all juniper trees. We use these findings to illustrate how a multiscale sampling design can increase prediction power, thereby improving our ability to provide resource professionals with critical values to target in management. Using such a strategy in this study revealed that fine fuel loading of 2 670 kg · ha⁻¹ were needed to scorch juniper trees 100% for the conditions present in the wet period, whereas only 1 280 kg · ha⁻¹ were needed in the dry period. To provide managers with this type of information, we suggest that researchers shift from simple, random sampling of fuels to alternate sampling designs where randomization is maintained in the designation of treatments or selection of observations (i.e., individual juniper trees) but where fuel is systematically sampled at the location of the observation of interest.

Resumen

Evaluamos la efectividad de diferentes estrategias de muestreo relacionándolas con la disponibilidad de combustible fino y el combustible quemado de la corona de los juníperos cenizo (*Juniperus Ashei*) y rojo (*Juniperus pinchotii*), por fuegos controlados efectuados durante periodos húmedos y secos de la época de crecimiento en las Edwards Plateau de Texas, USA. Nuestro objetivo era determinar si la variación espacial y temporal en el combustible quemado de la corona podía predecirse mejor por medio de las estimaciones de muestreo de disponibilidad de combustible con estrategias de muestreo explícito espacialmente a multi-escala o con el tradicional muestreo aleatorio simple de disponibilidad de combustible. Encontramos que el muestreo a nivel de multi-escala debajo y en áreas cerca a la corona del junípero fue más efectivo que el simple muestreo aleatorio para predecir el combustible quemado de la corona en los 14 fuegos realizados en el periodo húmedo y los cinco fuegos realizados en el periodo seco. El tipo de estrategia de muestreo que se empleó fue crucial para relacionar la disponibilidad de combustible y el combustible quemado de la corona durante el periodo húmedo. El volumen porcentual de la corona quemada varió de 0 a 100% bajo esas condiciones. En contraste, la estrategia de muestreo fue menos importante durante el periodo seco, cuando el combustible quemado de la corona sobrepasaba el 90% para todos los juníperos. Utilizamos estos resultados para ilustrar cómo un diseño de muestreo a multi-escala puede incrementar el poder de predicción, mejorando así nuestra habilidad de proporcionar recursos profesionales con valores críticos para objetivos de manejo. Utilizando tal estrategia en este estudio, concluimos que una disponibilidad de combustible fino de 2 670 kg · ha⁻¹ es necesaria para quemar 100% los árboles de junípero bajo las condiciones presentes durante el periodo húmedo, mientras que solo 1 280 kg · ha⁻¹ se necesitan durante el periodo seco. Para darles a los manejadores esta información, sugerimos a los investigadores cambiar del simple muestreo aleatorio de combustible al diseño alterno de muestreo, donde la aleatoriedad se mantiene en el diseño de los tratamientos o en la selección de las observaciones (como los arboles de junípero), pero cuando el combustible es muestreado sistemáticamente en el lugar de interés de observación.

Key Words: crown scorch, fuel load, functional scale, *Juniperus*, prescribed fire, random sampling

INTRODUCTION

A primary focus of research in fire ecology is to identify links among fuels, fire intensity, and fire effects. Numerous studies have investigated how fire intensity influences immediate fire effects (Albini 1976; Rothermel and Deeming 1980; Williams et

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al. 1998, 1999), and, more recently, fine-scale variation in fire intensity (i.e., differences in the heat produced by the fire over small distances, areas, or time) has been attributed directly to the presence and distribution of species in the postfire community (Thaxton and Platt 2006). However, limited research has identified how prefire heterogeneity in fuels influences localized variation in fire intensity and effects within a fire.

Juniper (*Juniperus* spp.) invasion into grassland results in localized variation in fine fuel load that may contribute to heterogeneous effects within a fire. Fine fuel is reduced beneath juniper crowns as the size and number of invaders increase (Engle et al. 1987; Smith and Stubbendieck 1990; Gehring and Bragg 1992) but varies depending on the amount of light penetration, allelopathic effects, and the abundance and distribution of shed juniper foliage (Engle et al. 1987). This, coupled with the spatial variation in fine fuel load that is inherent in many grassland systems, leads to complex surface fuels at fine scales. Such fine-scale heterogeneity in fuel load alters fire intensity and effects in low-intensity fires (Thaxton and Platt 2006), but traditional field sampling techniques (e.g., simple random) may not effectively detect and relate variation in surface fuel loads to fire intensity and fire effects.

The purpose of this study was to evaluate how effectively a simple random and two multiscale sampling strategies predict variation in fire intensity and crown scorch on juniper trees burned in wet and dry periods of the growing season. Although fire intensity was not measured directly in this study, crown scorch was assumed to be a proxy to fire intensity, an approach applied frequently in analyses of fire effects on conifer (*Coniferus* spp.) and juniper spp. (Van Wagner 1973; Rothermel and Deeming 1980; Engle and Stritzke 1995; Williams et al. 1998). Spatial variation in fire intensity was defined here as local differences in crown scorch that occurred within an experimental fire treatment and temporal variation in fire intensity as intraseasonal differences in crown scorch driven by wet and dry periods of the growing season. Sampling strategies were used to test the following hypotheses: 1) spatial variation in fuel load and fire intensity drive variation in crown scorch within burn treatments, and 2) this variation will be explained best by a sampling strategy that measures fuel load at a scale relative to individual juniper crowns.

METHODS

Study Area

This investigation was conducted at the Texas A&M University Agrilife Research Center located near Sonora, Texas, on the Edwards Plateau (Hatch et al. 1990). Annual precipitation is 670 mm (90-yr mean) with high interannual variability. 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, but continuity is disrupted by bare ground, rock outcrops, and woody encroachment of ashe juniper (*Juniperus ashei*), redberry juniper (*Juniperus pinchotii*), live oak (*Quercus virginiana*), and Vasey shin oak (*Quercus Pungens*; 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). Current juniper canopy cover and total woody canopy cover is approximately 20% and 40%, respectively (Smeins et al. 1997). Herbivory treatments were applied at light rates in 40-ha experimental units since 1998 as part of a long-term experimental design. Herbivory was excluded from experimental units for the duration of this experiment.

Experimental Design

Two fire treatments, wet-period versus dry-period fires, were applied to five 50-m transects in six of the long-term experimental units. Transects were established and assigned treatments randomly in each unit except that 1) transects were oriented in the direction of the prevailing wind (e.g., north-south) so that all transects burned as headfires, 2) transects were greater than 100 m apart to enable each transect to be lit independently, and 3) all transects were assigned the same fire treatment within each experimental unit to remain consistent with the long-term design of the site (see Fuhlendorf and Smeins 1997). Although the experiment was designed and sampled with equal replicates between treatments, environmental constraints precluded similar burn conditions on all 15 transects in each treatment, resulting in 14 burned transects for the wet period and five for the dry period.

Prefire Sampling

Individual juniper trees were sampled along each 50-m transect using the line-intercept method (Floyd and Anderson 1987). The location and aerial coverage was measured for each juniper crown that overlapped the transect. Juniper trees had to be ≥ 1.5 m tall and overlap with at least 1.5 m of the transect to be included in this analysis. Tree height and crown diameter were measured to the nearest 0.25 m.

Fine fuel load was estimated systematically in 100 0.5×0.5 m quadrats along each transect. Destructive sampling techniques that remove fine fuel were avoided to prevent human-induced alteration of fire behavior along transects. Instead, four fuel load classes (FLCs) were developed to estimate fine fuel load, similar to how vegetation cover is estimated as classes (Daubenmire 1959). With this technique, the amount of fuel in each quadrat was assessed visually and classified into an FLC of 0, 1, 2, or 3, with 0 and 3 representing the lowest and highest FLCs, respectively.

To determine if this technique was accurate and repeatable, FLCs were calibrated by randomly collecting fuel load samples in 50 0.5×0.5 m quadrats for each fire treatment. Fine fuel load was assessed visually in each quadrat and assigned to one of the four FLCs. The total live and dead fine fuel in each quadrat was clipped and collected, dried for 48 h at 70°C, and weighed to determine the actual dry weight of the fine fuel in each quadrat. The dry weight of each sample was then compared to the FLC predicted in the field. Regression analysis was used to determine the strength of the relationship (r^2) between FLC and fuel load. Fuel load class means were tested for significant differences using one-way analysis of variance.

Fire Application

Transects were burned in similar weather conditions in order to identify differences that were a result of the wet- and dry-period

fire treatments and not confounded by variation in environmental factors between treatments. Temperature ($^{\circ}\text{C}$), relative humidity (%), and wind speed ($\text{km} \cdot \text{h}^{-1}$) were monitored prior to and during implementation of the wet-period fire treatments. Weather conditions from wet-period fires were later targeted when fire treatments were implemented in the dry period of the growing season. Transects were burned in the dry period only after obtaining a weather forecast with similar estimates for temperature, relative humidity, and wind speed.

Each transect was burned with a 10-m wide head fire. A person with a drip torch lit a continuous fire front from a point 5 m west of the transect origin to a point 5 m east. Transects were burned for wet- and dry-period treatments on 13–14 July 2004 and 2 August 2005, respectively.

Sampling During the Fire

Fuel moisture and weather characteristics were measured at the time of ignition of each plot. Fine fuel moisture was quantified by clipping the total live and dead fine fuel material to ground level in five random 0.25-m^2 quadrats adjacent to each transect. Quadrats were not located within 5 m of each transect to prevent alteration of fire behavior via fuel removal. Fuel moisture samples ($n = 95$) were weighed immediately on clipping, oven dried at 70°C for 48 h, and then reweighed to calculate fuel moisture on a dry-weight basis. Juniper foliar moisture content was measured for two juniper trees per transect by collecting foliage from the terminal 0.2 m of branches at a height of 1.0–1.5 m above the soil surface. Temperature ($^{\circ}\text{C}$), relative humidity (%), and wind speed ($\text{km} \cdot \text{h}^{-1}$) were measured 30 m downwind of the transect origin at a height of 1.5 m using a Kestrel 4000 (Nielson-Kellerman, Boothwyn, PA), a weather data logger, from the time the fire was ignited to the time the fire either reached the end of the transect or ceased to spread within the transect.

Postfire Sampling

Aboveground fire effects were quantified 2 wk following each fire by visually assessing percent crown volume scorched to the nearest 10% for all juniper trees that intersected each transect. Percent crown volume scorched was used instead of scorch height because it is a more accurate estimate of crown scorch (Peterson 1985), and scorch height does not describe scorch effects when numerous trees are scorched completely.

Comparison of Fuel Sampling Strategies

Measures of fine fuel load along the transect were used to develop three distinct sampling strategies to determine which strategy best predicted crown scorch within each fire treatment. The difference between sampling strategies was how quadrats were combined to generate a fuel load sample. Quadrats along the transect were aggregated to coalesce fuel load values 1) at random, 2) at arbitrary scales of measurement about each individual tree, and 3) at functional scales of measurement about each individual tree (Table 1). Aggregate fuel load values were used to correlate juniper crown scorch with fire intensity. Fine fuel load was used as an independent variable for correlating juniper crown scorch with fire intensity since fine fuel consumption was 100% in all cases where fine fuel was consumed in the experimental burns.

A simple random sampling strategy was established to evaluate fuel sampling techniques that are typically applied in field studies of fire effects (Table 1). In a simple random sampling strategy, fuel loads are measured at random locations, and the results are extrapolated to represent the mean fuel load of the entire area (e.g., Bidwell and Engle 1992; Engle and Stritzke 1995; Briggs et al. 2002; Streeks et al. 2005). Monte Carlo simulation was used to randomly select 10 quadrats along the transect. Fuel load values within those quadrats were averaged to obtain the mean fuel load for each transect. Next, the mean fuel load for that transect was coupled with the juniper tree located on that same transect. This process was repeated for all juniper trees within each fire treatment (e.g., seven trees for wet period, 10 trees for dry period) to calculate the correlation (r) between the randomly derived mean fuel load and juniper crown scorch for each fire treatment. Simulations were then repeated, thereby coupling 10 new quadrats with each juniper tree to calculate an additional correlation (r) between the randomly derived mean fuel load and juniper crown scorch. Simulations were repeated 1500 times. Variability among correlations was evaluated to determine the repeatability of a simple random sampling design.

The second sampling strategy used in this study related the juniper crown to the fuel load that occurred at arbitrarily selected spatial scales about the midpoint of the crown (Table 1). An arbitrarily based multiscale sampling strategy is frequently applied when studies aim to quantify and link process–pattern relationships within heterogeneous environments (O’Neill et al. 1989, 1991). Arbitrary spatial scales were chosen by aggregating fuel load attributes of individual quadrats located at equidistant intervals from the canopy midpoint of each juniper tree. Aggregation of fuel load values began at a distance of 1.0 m and increased at 0.5-m intervals until reaching a final scale of 15.0 m. Variation (r^2) in crown scorch explained by the mean fuel load at each arbitrary scale was then calculated to determine the scale(s) that best predicted crown scorch in wet- and dry-period fire treatments.

The final strategy used in this study identified functional scales between fuel load and the juniper crown (Table 1). Functional scales were selected by considering 1) the extent to which fuel load is influenced by the juniper overstory crown, 2) how to choose a scale when tree sizes varied considerably as in this study, and 3) the potential for crown scorch to be influenced by fire intensity as a function of the fine fuel load occurring underneath and near juniper trees. We therefore chose four functional scales that depict quadrats corresponding to the intercept of the juniper crown along the transect and at lag distances of 1 m, 2 m, and 3 m outside the crown intercept. Subsequently, functional scales were variable scales driven by differences in the size of each individual tree. These data were used to evaluate whether the functional sampling strategy to choosing a scale could improve juniper crown scorch prediction in comparison to multiple scales selected arbitrarily. Significant differences in the predictive ability of the functional and arbitrary sampling strategies were tested using a two-way analysis of variance with the Bonferroni correction (Benjamini and Hochberg 1995).

To determine which sampling strategy was most reliable in relating fuel load to crown scorch, correlation coefficients (r) produced with the simulation of the simple random sampling

Table 1. Description of how fuel loads were related to juniper crowns 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 crown scorch at various resolutions by averaging 0.5-m plots at random or at the specified spatial scale.

Sampling technique	Resolution (m)	No. of 0.5-m plots	Scale dependence between fuel load and juniper crown
Simple random	50.0	10	None; samples collected at random
Arbitrary scales	1.0	2	Samples summed at the crown midpoint
	1.5	3	Samples summed in equidistant directions from crown midpoint
	2.0	4	Samples summed in equidistant directions from crown midpoint
	—	—	—
	—	—	—
	—	—	—
Functional scales	14.5	29	—
	15.0	30	—
	1.5–6.0	Varies	Samples summed at crown intercept and vary with crown size
	1.5–7.0	Varies	Samples summed at crown intercept plus 1 m from edge of crown and vary with crown size
	1.5–8.0	Varies	Samples summed at crown intercept plus 2 m from edge of crown and vary with crown size
	1.5–9.0	Varies	Samples summed at crown intercept plus 3 m from edge of crown and vary with crown size

strategy were compared to those produced by arbitrary and functional sampling strategies at the scale that best predicted the relationship. Strategies were compared by identifying the number of times the random strategy produced a correlation coefficient that exceeded that of the multiscale strategies. A probability level of 0.05 was established for this test, meaning that the correlation coefficient of the arbitrary and functional strategies had to exceed 95% of the correlation coefficients produced by the simple randomized strategy.

RESULTS

Fuel Load Classes

Fuel loading (class mean \pm SE) of 107 ± 12 , 978 ± 36 , 2203 ± 53 , and 4062 ± 102 $\text{kg} \cdot \text{ha}^{-1}$ represented FLCs of 0, 1, 2, and 3, respectively. One-way analysis of variance revealed class means to be significantly different ($P < 0.001$ for all class means). The strength of the relationship (r^2) between FLC and fuel load was 0.90 ($P < 0.0001$).

Fire Prescriptions

Temperatures were not significantly different between fire treatments. Minimum and maximum values were 28.5 and 38.5°C in the wet period, respectively, compared to 33.5 and 38.4°C in the dry period, respectively. Relative humidity was higher in the dry period ($P < 0.01$) with lower and upper limits of 22.9–26.1% in the dry period and 12.4–29.1% in the wet period. Wind speed, juniper foliage moisture, and fine fuel moisture were lower in the dry period ($P < 0.01$, 0.05, and 0.0001, respectively). Wind speed ranges were 1.0–3.1 $\text{km} \cdot \text{h}^{-1}$ in the dry period compared to 3.2–11.6 $\text{km} \cdot \text{h}^{-1}$ in the wet period. Juniper foliage moisture content ranged from 42.0–80.9% in the dry period versus 70.0–128.0% in the wet period. Fine fuel moisture limits were 3.0–8.5% in the dry period as opposed to 12.7–29.3% in the wet period.

Sampling Comparisons

The functional sampling strategy explained the greatest amount of variation in crown scorch during the wet period at the scale of the crown intercept ($r^2 = 0.81$, $P < 0.05$). The ability for other functional scales to explain variation in crown scorch decreased at increasing distances from the crown (Fig. 1). An arbitrary sampling strategy produced similar results. Crown scorch was explained more effectively by finer scales of resolution than those scales that included fuel load measurements further away from juniper crowns (Fig. 2). The greatest amount of variation explained by the arbitrary sampling strategy was 76% at spatial scales of 5.5 m and 6.0 m. Alternatively, fuel load was a poor predictor of crown scorch during the dry period, regardless of spatial scale or sampling technique (Figs. 1 and 2). Crown scorch was independent of the amount and distribution of fine fuel load in these conditions. All juniper trees were scorched $> 90\%$. Arbitrary and functional strategies were significantly superior to simple random sampling in both fire treatments ($P < 0.001$ and 0.05 for functional strategy in wet and dry treatments, respectively; $P < 0.05$ for arbitrary strategy in wet and dry treatments). Correlations (r) between crown scorch and fuel loads sampled with a simple random strategy ranged from < 0.01 to 0.93 in wet-period fires and from < 0.01 to 0.65 in the dry period.

The critical amount of fine fuel needed to completely scorch juniper trees was derived using the functional sampling strategy for the fuel and weather conditions present during this study. In the wet-period fire treatment, all juniper crowns were scorched 100% when fine fuel load was ≥ 2670 $\text{kg} \cdot \text{ha}^{-1}$, whereas only 1280 $\text{kg} \cdot \text{ha}^{-1}$ were needed in the dry period to cause the same effect (Fig. 1A).

DISCUSSION

Sampling within the immediate vicinity of juniper crowns using functional and arbitrary sampling strategies was more effective

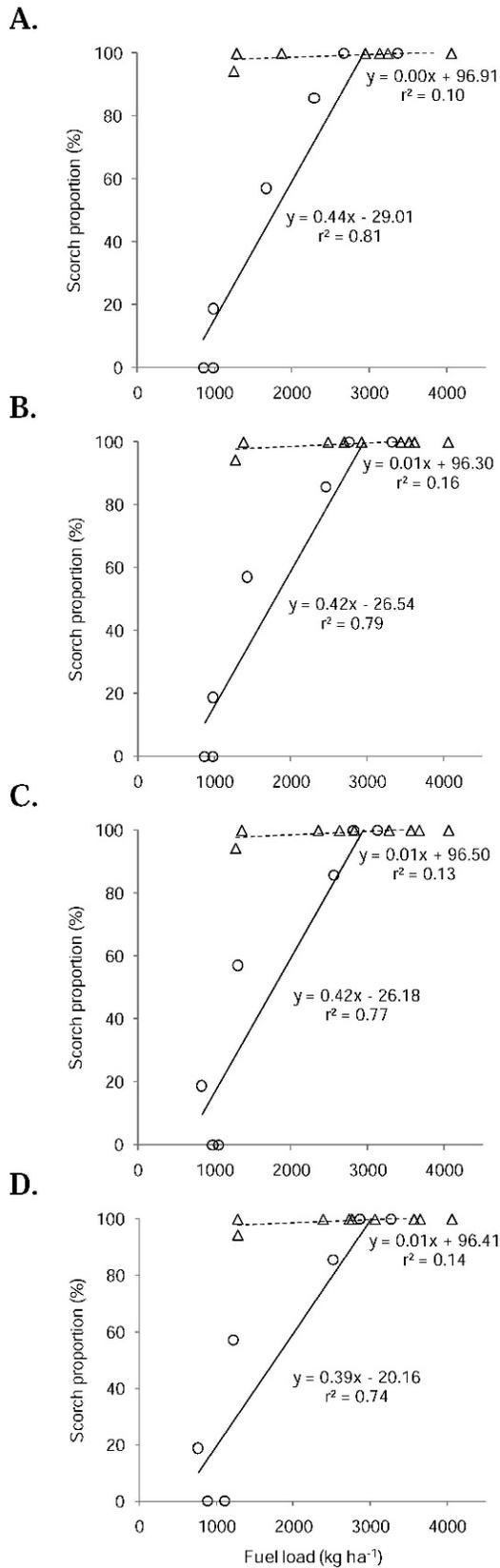


Figure 1. Relationship between crown scorch and the mean fuel load sampled about the juniper crown with a functional sampling strategy during wet-period (shown as circle with solid line) and dry-period (shown as triangle with dashed line) fire treatments. Functional scales corresponding to **A**, the crown intercept and at lag distances of **B**, 1.0 m, **C**, 2.0 m, and **D**, 3.0 m from the crown intercept are shown.

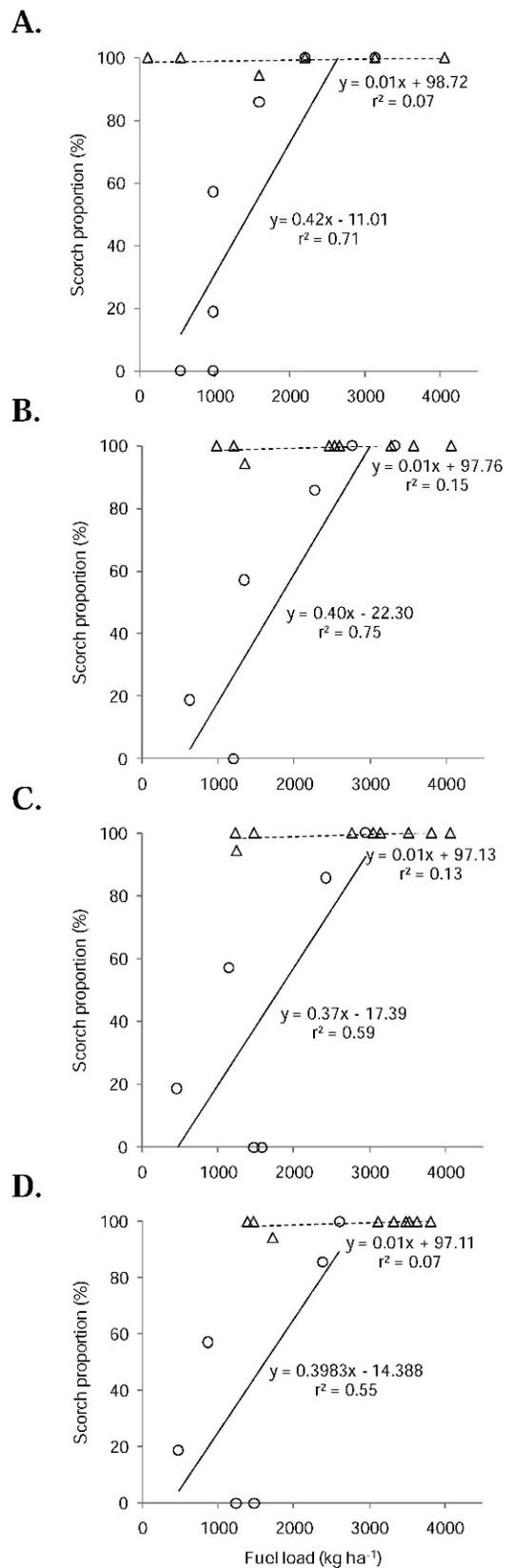


Figure 2. Relationship between crown scorch and the mean fuel load sampled about the juniper crown with an arbitrary sampling strategy during wet-period (shown as circle with solid line) and dry-period (shown as triangle with dashed line) fire treatments. Selected for illustration were arbitrary scales of **A**, 1.0 m, **B**, 5.0 m, **C**, 10.0 m, and **D**, 15.0 m.

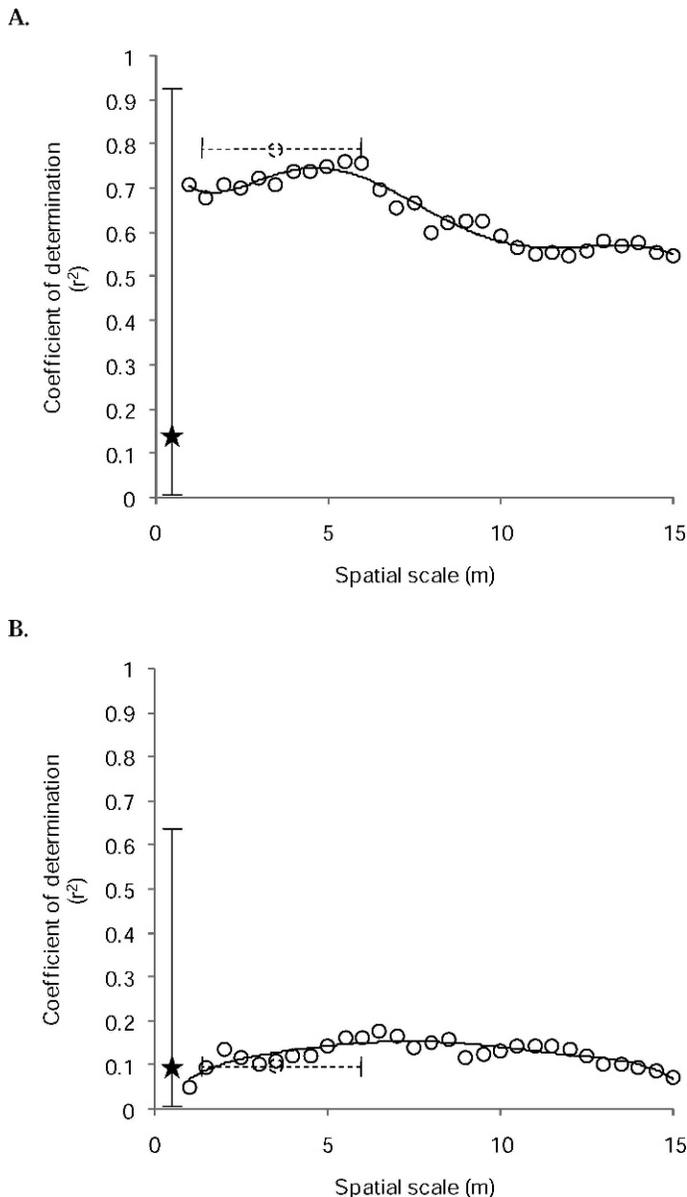


Figure 3. Illustration comparing the amount of variation in crown scorch explained by the mean fuel load sampled using simple random (vertical bar), arbitrary (solid line), and functional (dashed line) sampling strategies for fires conducted in **A**, wet-period fires and **B**, dry-period fires. Only the functional scale corresponding to the crown intercept is shown here. Note that the star and surrounding bar represent the average and range, respectively, in correlations between crown scorch and random fuel load samples selected using Monte Carlo simulation.

than simple random sampling in predicting crown scorch for both wet- and dry-period fire treatments. Such findings demonstrate that a transition in field sampling is needed to identify causal relationships linking fuels, fire behavior, and fire effects in heterogeneous systems. Field methods need to be consistent and produce repeatable results to make valid interstudy comparisons, something traditional, simple random sampling techniques were unable to produce in this heterogeneous environment (Fig. 3). The vast range of correlations produced in both wet- and dry-period fire treatments when using such a strategy demonstrates that two studies could have

identical fuel characteristics, fire behavior, and fire effects yet still yield dramatically different results. In search of more consistent results, studies in other ecological subdisciplines have employed a multiscale approach (O'Neill et al. 1989, 1991; Turner 1989; Wiens 1989) to overcome potential problems that arise when analyzing process–pattern relationships in heterogeneous environments. We used such an approach to design a multiscale assessment of arbitrarily and functionally defined relationships between fuel load and crown scorch as the fire environment changes from mild (e.g., wet period) to extreme (e.g., dry period). The type of sampling strategy employed was less important in the dry period, when low moisture contents of fine fuels and juniper foliage were more dominant drivers than fuel load, resulting in high levels of crown scorch for all fuel loads ranging from 1000 $\text{kg} \cdot \text{ha}^{-1}$ to 4200 $\text{kg} \cdot \text{ha}^{-1}$ (Figs. 1 and 2). Conversely, sampling strategy was critically important in relating scorch to fuel load in wet-period fires for a similar range of fuel load values (Figs. 1 and 2).

Although the use of a simple random sampling strategy has been a staple of fire effects–related research, transitioning to an alternate strategy that is more effective in the presence of heterogeneity should be relatively straightforward. The primary problem with simple random sampling in heterogeneous systems is that samples are collected arbitrarily at locations independent from the observation of interest. Alternate experimental designs and sampling approaches, such as stratified random sampling (Gillison and Brewer 1985; Fortin et al. 1989) or nonrandom spatially autocorrelated designs (Fortin et al. 1989; Legendre 1993; Dale 1999; Fortin et al. 2002; Fortin and Dale 2005), maintain randomness by randomly selecting individual observations (e.g., individual trees) and then sampling the factors that drive the effect (e.g., fuel, fire intensity) at that location. Since fuel load under the juniper crown was the most appropriate scale of measurement for the conditions in this study (Fig. 3), one can envision a more intricate design that nests a sampling grid about each juniper tree such that pattern in fuel load can be derived at multiple spatial scales and then related to juniper crown scorch. Such a design may prove useful in accounting for fine-scale variation in other fuel characteristics that may interact with variation in fine fuel load to alter fire intensity and effects at local scales. Spatial variation in fuel moisture, for example, may increase variation in effects within a fire (Peet and Allard 1993; Drewa et al. 2002; Knapp and Keeley 2006). Additionally, higher wind speeds, variable topography, and localized differences in surface fuel types, among other factors, may be important drivers of spatial variation in fire behavior and effects. Sampling designs that can account for these sources of variation at multiple scales have the potential to identify the relative importance of fine fuel load versus other factors in driving spatial variation in fire intensity and fire effects.

MANAGEMENT IMPLICATIONS

Quantifying spatial and temporal drivers of fire effects can improve applications of research in management (Williams et al. 1994). For example, a critical amount of fine fuel is currently identified as the primary driver of scorch and

mortality of juniper trees in rangelands (Fuhlendorf et al. 1996; Briggs et al. 2002, 2005). In this study, however, all juniper trees were completely scorched in the dry-period fire treatment, regardless of the amount and distribution of fine fuel load (Fig. 1A). Multiple pathways therefore exist for resource professionals attempting to use fire to manage and restore rangelands. While this study was not established to provide an exhaustive depiction of mechanisms of crown scorch, it does illustrate how researchers can provide managers with precise information on the factors required to completely scorch juniper crowns. For fires conducted in the fuel and weather conditions of the wet-period treatment, managers should target a fine fuel load value of 2 670 kg·ha⁻¹ that occurs beneath juniper trees (Fig. 1A). In contrast, managers need only 1 280 kg·ha⁻¹ when fires are conducted in the fuel and weather conditions present during the dry-period treatment (Fig. 1A). With this information, managers will be able to target specific values from an array of environmental drivers, ultimately leading to more successful management in rangeland systems.

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