MODELING SPATIAL PATTERNS OF FUELS AND FIRE BEHAVIOR IN A LONGLEAF PINE FOREST IN THE SOUTHEASTERN USA

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ABSTRACT

Characterizing spatial patterns of fire behavior is an important and rarely considered means of understanding patterns of vegetation recovery following a fire event. Using geostatistics, we characterized spatial patterns of pre-burn fuel loads, fire temperature and duration during prescribed burns, and post-burn fuel loads in four longleaf pine stands in the southeastern USA. Fire temperatures exhibited moderate to strong spatial dependence over medium spatial scales. Variograms suggest that 61-99% of sample population variance was spatially dependent at scales of 27-157 m. Patterns of pre-burn fuel loads were only moderately related to patterns of mean fire temperature, confirming that fuel loads alone cannot predict fire patchiness. Other fuel parameters and microscale changes in wind and relative humidity likely influenced patterns of fire intensity as well. Strength and scale of fuel load spatial patterns were altered by fire as indicated by pre- and post-burn measurements. Spatial analysis provides a useful way to quantify burn patchiness and can help to identify which patch size may be desirable for different management goals. Studies that examine fire effects need to recognize spatial autocorrelation when characterizing fire behavior and account for this variation at appropriate scales.

Key-words: *fire ecology, geostatistics, prescribed burning, burn heterogeneity, spatial autocorrelation.*

INTRODUCTION

Characterizing spatial patterns of fire behavior is an important and rarely considered means of understanding patterns of vegetation recovery following a fire event. Research conducted in temperate forests suggests fires may have widely varying effects on forest regeneration (Whelan 1994, Bond and van Wilgen 1996). For example, low intensity fires may have a positive effect on regeneration by increasing available soil nutrients (DeBano et al. 1977, Wright and Bailey 1982), and stimulating flowering (Whelan 1994, LeMaitre and Brown 1992), resprouting (Zedler et al. 1983), and seed germination (Schimmel and Granstrom 1996; Bradstock and Auld 1995). In contrast, high intensity fires may be detrimental to regeneration by volatilizing available nutrients (Wright and Bailey 1982), altering soil properties such as texture, cation-exchange capacity, and water holding capacity (DeBano et al. 1977), and killing seeds (Schimmel and Granstrom 1996), sprouts (Kennard et al. 2002), and potential seed trees (Dickinson and Johnson 2001).

Fire behavior varies over spatial scales depending on local differences in fuel loads, moisture, and wind (e.g., Albini 1976). Fuel consumption is expected to vary over spatial scales due to both the patchy distribution of plant biomass and necromass and the percentage of this material that is considered available fuel (Hobbs and Atkins 1988). Fuel moisture largely determines fuel availability, and dead fuel moisture varies spatially according to topography, canopy openness, and microclimate (Robichaud and Miller 1999). Weather conditions such as wind speed and relative humidity often vary over the course of a burn and can also translate into spatial variation in fire behavior.

This spatial variation in fire behavior (i.e., patchiness) is a characteristic feature of most fires, and provides a critical mechanism to alter spatial patterns of vegetation recovery following fire. For example, both Rice (1993) and Odion and Davis (2000) found that patterns of fire intensity shaped patterns of plant regeneration in California chaparral. Franklin et al. (1997) found that the patchiness of burns influenced vegetation response in upland oak communities in the central hardwoods of the USA. However, no studies have yet explored these questions in the fire-prone ecosystems of the southeastern coastal plain of the USA. More than 8 million acres of land are burned annually in this region, more than all other regions of the USA combined (Wade et al. 2000).

We examined spatial patterns of fuels loads, fire temperature and duration, and post-fire fuel accumulation in a longleaf pine (*Pinus palustris* Mill.) forest in the Gulf coastal plain of the southeastern USA. Longleaf pine forest was once one of the most extensive forest ecosystems in North America, dominating as much as 37 million ha in the southeastern USA at the time of European settlement (Frost 1993). Today it occupies less than five percent of its original range, making it one of the most endangered ecosystems in the USA (Noss et al. 1995). Longleaf pine ecosystems are among the most species-rich plant communities outside the tropics (Peet and Allard 1993). Its continued loss has a prompted an organized effort to restore and manage remaining fragments. A vital component of longleaf restoration and management is prescribed burning. Longleaf pine is one of the most fire dependent ecosystems in North America, requiring frequent (1-6 years) low-intensity surface fires (Frost 1998). While a tremendous amount of knowledge has been accumulated on the effects of fire on longleaf pine systems (e.g., Kush et al. 1996), no studies have examined the question of spatial dependence in fuels, fire behavior, or post-fire vegetation recovery.

Semivariance-analysis provides a means for examining autocorrelation in environmental data (e.g., Robertson and Gross 1994). This technique documents whether there is a spatial component to the variability (is there patchiness?) and the robustness of the pattern (how distinct are the patches?). In addition, semi-variance analysis also reveals over what scale autocorrelation occurs (patch size; Isaacs and Srivastava 1989). Using this technique, we explored the following questions:

- Does the variation in fuel loads and fire behavior have a distinct spatial component?

- If so, over what spatial scales do patterns of these variables vary?
- Do fuel loads and fire behavior show similar spatial patterns?
- Does fire behavior and post-fire fuel accumulation show similar spatial patterns?

Semivariance analysis is an exploratory technique used to characterize spatial patterns- it does not require replication (Robertson et al. 1997). In fact, no published fire studies using this technique or similar spatial analyses have examined more than one burn of the same prescription (Rice 1993, Franklin et al. 1997). In this study, we examined the questions above in six fires, which allows a more reliable assessment of this analysis technique and a more robust interpretation of the results.

METHODS

Site description

This study was conducted in naturally regenerated longleaf pine stands at the Solon Dixon Forestry Education Center (DFEC), in the lower coastal plain of Alabama, USA. Moist air from the Gulf contributes to the area's short, cool winters and long, hot summers. Average summer and winter temperatures are 26^{o} C and 9^{o} C, respectively. Annual precipitation is 148 cm. Soils are deep and well-drained sandy loams that are strongly to very strongly acidic with low organic matter.

The data used in this study were collected during prescribed burns of 4 experimental plots (10-20 ha each) of the Fire-Fire Surrogate (FFS) Study (http://www.fs.fed.us/ffs). The FFS Study uses a common experimental design at 13 sites across the United States to compare the ecological and economic consequences of fuel reduction treatments: an untreated control, mechanical treatments, prescribed burning, and a combination of mechanical treatments followed by prescribed burning. The Gulf Plain FFS at the DFEC has an additional fifth treatment of an understory herbicide application followed by prescribed burning. All plots used in the FFS study were located in upland longleaf pine stands managed with early-growing season burns on a three-year rotation since the mid-1970s. In this study, we examined spatial autocorrelation of fuels and fire behavior in 4 plots: 1 burn-only plot and 3 herbicide-and-burn plots. (While we also collected data in 2 additional burn-only plots, the disjunct configuration of these 2 plots made the results of the spatial analysis unreliable; therefore, we focus this paper on the results of the 4 contiguous plots.) The broader implications of how the four fuel reduction treatments in the FFS study affect actual fuel loads and reduce the risk of catastrophic wildfire, the primary objective of the FFS study, will be discussed in a separate paper.

The burn-only treatment plot was burned in April of 2002. Understory fuels in the herbicide-and-burn treatment plots were treated with herbicide in the fall of 2002 and burned April-May 2003. Plots were burned with a combination of backing fires and spot fires, with distance between spots ranging from 20-50 m. In the burn-only plot, the wind shifted and the fire developed into a flanking then heading fire. Weather conditions and general fire behavior for each burn are displayed in Table 1.

Field methods

There are few practical methods of measuring fire behavior in the interior of a fire at landscape scales (e.g., Iverson et al. 2004). In this study we used two relatively inexpensive devices, pyrometers

Table 1. Weather conditions and fire behavior during prescribed burns in four plots conducted in the spring of 2002 and 2003 in a longleaf pine forest in southern Alabama, USA.

Treatment	Plot	Date	Total burn time (hrs)	Max. ambient air temp (C)	Average RH (%)	Minimum RH (%)	Wind direction/ speed (km/hr)	Average Rate of Spread (m/hr)	Average Flame Length (m)	Average Fire Zone Width (m)	Average Residence Time (min)
Burn-only											
	6	4/17/2002	6	32	45.4	38	var / 8-10	62	1.1	0.9	4.8
Herbicide-and-burn											
	4	4/15/2003	9	29	34.4	25.0	SE / 2-3	39	0.7	0.7	3.8
	12	4/16/2003	10	29	38.1	29.0	S,SW / 3-5	57	1.6	0.9	4.3
	7	5/13/2003	8	29	31.5	22.0	NE / 8				

and can calorimeters, which allowed us to sample both intensively and extensively. As described in detail below, we developed an index that incorporates both fire temperature and duration (referred to as “mean fire temperature”) from the information gathered from pyrometers and can calorimeters. While we realize each of these measuring devices have inherent limitations (see Iverson et al. 2004, Kennard et al. 2005, and Walley et al. in press) and that mean fire temperature *per se* is not as useful a parameter to model as fireline intensity, for the purposes of this paper we are more interested in the *variation* of fire behavior over spatial scales (relationship *between* points) rather than the value of measurements at individual points. Other indicators of fire behavior, such as flame length, residence time, or fireline intensity, would also have provided information on spatial autocorrelation in fire behavior. However, the logistics and cost of measuring these other parameters in the interior of a fire at a landscape scale far exceeded those posed by using pyrometers and calorimeters.

In each treatment plot, fuel loads and mean fire temperatures were estimated at 100 spatially referenced sampling points. Sampling points were arranged as systematic clusters. This sampling design is more capable of detecting spatial structures than regular grids (Fortin et al. 1989). The minimum distance between sampling points was 1 m. The maximum distance between sampling points varied due to plot configuration and ranged from 375 to 575 m.

Pre-burn fuel loads were estimated 3 weeks before burns in 1x1 m subplots centered on sampling points. Standing fuel loads were estimated by the percent covers and average heights of live trees/shrubs, dead trees/shrubs, vines, grasses, and forbs. Biomass for these various fractions was calculated from regression models derived from an additional 150 1 m^2 plots that were destructively sampled and the dry masses determined: live tree/shrub (biomass g [ln+1] = 0.552 volume (cm^3) + 0.104, r^2 = 0.63); dead tree/shrub (biomass g [ln+1] = 0.462 volume (cm^3) + 0.295, r^2 = 0.52); vines (biomass g [ln+1] = 0.423 volume (cm^3) + 0.515, r^2 = 0.53); grasses (biomass g [ln+1] = 0.475 volume (cm^3) + 0.360, r^2 = 0.53); and forbs (biomass g [ln+1] = 0.420 volume (cm^3) + 0.100, r^2 = 0.54). Litter depth (O_i) was measured in the center of each subplot (pre-burn plots contained very little duff, Oe and Oa horizons). Litter mass per subplot was calculated from depth using a litter density of 0.039 g/cm^3 derived from 900 destructively sampled subplots (929 cm^2 or 1 ft^2). In a 1 m transect bisecting the subplot, the number of intercepts of fuels in four size classes (0-.6 cm, > .6 – 2.5 cm, > 2.5 – 7.6 cm, > 7.6 cm) were used to calculate masses of down dead woody fuels using Brown's fuel equations (Brown 1974). Immediately following fires, the percent burn of each subplot was visually estimated. Post-burn fuel loads were estimated five months after burns at the end of the first growing season using the methods described above in the burn-only plots. Due to the generally weak relationship found between fire temperature and the accumulation of fuels post-burn in these plots (discussed in results) and the likely confounding factor herbicide application would have on these patterns, post-burn fuel loads were not measured in the three herbicide-and-burn treatment plots.

Fire temperature and heat output was estimated at 30 cm height in the center of each 1x1 m subplot using pyrometers and calorimeters. Because our interest in this paper is to describe the autocorrelation between measured points, we discuss the advantages and limitations of these techniques in a different paper (Kennard et al. 2005, see also Iverson et al. 2004, Walley et al. in press). Briefly, pyrometers were made by applying Tempilaq ® heat indicating lacquers (Tempil Division, Big Three Industires, Inc., South Plainsfield, NJ, USA) to steel cans. Based on previous burns, we selected 14 lacquers that melted over a range of temperatures from 175 -800^o F (79 -427 ^{o} C) at increments of 50 ^{o} F (28 ^{o} C) from 200 ^{o} F and higher.

Calorimeters (steel cans) were wired to metal stakes at 30 cm height. Before burns, 50 ml of water was added to each can. After prescribed burns were completed, cans were capped, collected, and transported to the lab where remaining water was measured with a graduated cylinder or weighed. For each burn, 2-3 control calorimeters were placed in unburned areas to account for ambient evaporation. The amount of water vaporized from caloriometers during burns (accounting for ambient evaporation) was used to calculate heat output of flames as: heat output = [(80 ca/g water) x (g water)] +[(540 cal/g water) x (g water)], where 80 cal are needed to raise each gram of water from 20^o C to boiling point and 540 cal are need to vaporize each gram of water (Beaufait 1966).

At 20 points in each plot, pyrometers and calorimeters were compared with HOBO® Type-K thermocouple loggers equipped with high temperature stainless-steel Type-K thermocouple probes (Onset Computer Corporation, Cape Cod, MA, USA). Each probe consisted of a 304 stainless steel jacket packed with MgO, 30.5 cm long and 4.8 mm in diameter, with an isolated Type K thermocouple junction at the tip. Due to their thickness and thermal characteristics, these probes have long response times and residence times (Iverson et al. 2004). They have also proved useful in estimating fireline intensity (Bova and Dickinson 2003). We found that temperature (as indicated by the pyrometer) and heat output (as indicated by the calorimeter) estimated the one-minute mean about the instantaneous maximum fire temperature derived from the thermocouples (Perez and Moreno 1998, Walley et al. in press, Kennard et al. in review) well (R^2 = 0.62 to 0.92, n = 20 per plot). Equations derived from these regressions were used to calculate what we refer to as “mean temperature” at each of the 100 points sampled.

ANALYSIS

Standard parametric analyses were performed with SPSS (SPSS 1998). Semi-variance analyses of fuels and fire temperature were performed using GS+ (Gamma Software Design 1994). Semi-variance analysis calculates the degree of variation between all locations in a spatial domain separated by the same distance (the “semi-variance”). The result is a semi-variogram that plots the semi-variance over all distance intervals. Where variation is spatially dependent, the semi-variance typically rises to some asymptote, termed the “sill,” which should approximate the population variance. The y-intercept of the semi-variogram represents either random sampling error or spatial dependence at distance intervals less than the minimum interval sampled. The distance from the sill to the y-intercept is the amount of variance explained by spatial patterning. For the purposes of comparing semivariograms for both variables within a plot and between plots, we used the same model parameters (range and separation distance classes) for all semivarigram calculations. Although a range of 400-600 m is possible for data from these plots, all models were fit across a range of 200 m due to the low number of pairs beyond this range. Semivariance pairs were grouped into five separation distance classes (lag classes) between 0 and 200 m. Average distance between points of a pair was 1, 16, 49, 96, and 164 m, respectively. Best fit models were chosen based on r^2 values, reported in the results. Maps based on these best fit models were produced with GS+ following point kriging.

To help explain the results found using semivariance analysis, we also ran stepwise multiple regressions. We tested how well pre-burn fuel components (mass of standing fuel, litter mass, and 1, 10, 100, and 1000 hour fuels) predicted mean fire temperature. We also tested how well pre-burn fuel components (mass of standing fuel, litter mass, and 1, 10, 100, and 1000 hour fuels) and mean fire temperature predicted post-burn standing fuel mass. Multiple regressions were performed using SPSS v. 9.0 (SPSS, Inc. 1998).

Table 2. Means of pre-burn fuel loads, “mean fire temperature”, and post-burn fuel loads (burn-only plots) for 4 plots burned in the spring of 2002 (burn-only plot) or 2003 (herbicide-and-burn plots) in a longleaf pine forest in the southeastern USA (SD in parentheses).

			Pre-burn			*Post-burn*		
		Litter mass	Standing fuel mass	Woody debris mass	“Mean fire temp.”	Litter mass	Standing fuel mass	Woody debris mass
Treatment	Plot	g m-2	g m-2	g m-2	C	g m-2	g m-2	g m-2
Burn-only								
	6	1486 (956)	159 (58)	496 (814)	164 (75)	850 (437)	84 (56)	434 (634)
Herbicide-and-burn								
	4	1151 (640)	242 (73)	160 (337)	154 (70)			
	7	1136 (693)	204 (78)	106 (238)	156 (62)			
	12	1099 (488)	188 (89)	188 (381)	236 (212)			

Table 3. Variogram model parameters for pre-burn fuel components, mean fire temperature, and post-burn fuel components (burn-only plot) of plots burned in the spring of 2002 or 2003 in a longleaf pine forest in the southeastern USA.

			Effective Range	Relative structure	Model fit	Nugget	Sill	Sample variance
		model	(m)	$C/(C + C_o)$	r^2	C_o	$C + C_o$	s^2
Burn-only								
Plot 6								
	Mean fire temperature	exp.	27	0.95	0.95	0.05	0.89	5733
	Pre-burn standing biomass	exp.	10	0.99	0.96	0.00	1.06	3430
	Pre-burn litter mass	exp.	*	0.50	0.01	0.70	1.39	914718
	Pre-burn 1-1000 hour fuel mass	spher.	131	0.65	0.99	0.44	1.25	662855
	post-burn standing biomass	exp.	494	0.50	0.51	0.74	1.48	3089
	post-burn litter mass	exp.	51	0.97	0.97	0.03	0.99	185987
	post-burn 1-1000 hour fuel mass	exp.	511	0.50	0.06	0.89	1.77	404285
Herbicide-and-burn								
Plot 4								
	mean fire temperature	exp.	157	0.61	0.80	0.44	1.13	6002
	Pre-burn standing biomass	exp.	*	0.50	0.03	0.90	1.80	5196
	Pre-burn litter mass	spher.	21	0.99	0.95	0.00	1.14	403636
	Pre-burn 1-1000 hour fuel mass	spher.	21	0.94	0.89	0.07	1.12	112489
Plot 7								
	mean fire temperature	exp.	50	0.65	0.93	0.35	1.00	3831
	Pre-burn standing biomass	spher.	20	0.80	0.99	0.20	1.03	16.65
	Pre-burn litter mass	exp.	48	0.89	0.99	0.11	1.01	164076
	Pre-burn 1-1000 hour fuel mass	exp.	*	0.50	0.01	0.90	0.18	57121
Plot 12								
	mean fire temperature	exp.	137	0.99	0.98	0.02	1.28	44879
	Pre-burn standing biomass	exp.	56	0.96	0.94	0.04	1.06	8450
	Pre-burn litter mass	exp.	*	0.50	0.70	0.66	1.31	238176
	Pre-burn 1-1000 hour fuel mass	linear	#	0.00	0.24	1.34	1.34	145911

* effective range beyond the range of study plot

no spatial structure detected ($C/ (C+ C_o) = 0$)

RESULTS

Mean fire temperatures ranged from 154 -236 ^{o} C (Table 2). Plot 12 had the highest mean fire temperatures, averaging 236^{o} C. Variogram results (Table 3, Figure 1) suggested that mean fire temperatures exhibited moderate to strong spatial dependence; 61-99% of sample population variance of mean fire temperature is spatially dependent (relative structure or $C/(C + C_o)$ in Table 3) at scales of 27-157 m (effective range). Kriged maps of mean fire temperatures are shown for plots four, six, seven, and 12 in Figures 2 to 5. Pre-burn fuel components were strongly spatially autocorrelated in some plots, although not consistently across all plots and fuel components (Table 3). For example, pre-burn standing biomass in three of four plots exhibited strong spatial dependence; variograms suggest that 80-99% of sample population variance was spatially dependent at scales of 10-56 m. However, only 50% of the variation in pre-burn standing fuel mass in Plot 4 was explained by spatial variation, and this variation was at scales larger than the sample area. In two plots, 89-99% of litter mass variance was spatially dependent at scales of 21-48 m, however only 50% of variation was spatially dependent in the other two plots.

Figure 1. Sample variograms for mean fire temperature, pre-burn litter mass, pre-burn standing biomass, and pre-burn 1-1000 hour woody fuels in a longleaf pine stand burned in 2003 (Plot 7). Dotted lines indicate overall sample variance. Model parameters for these variograms and all others (not shown) appear in Table 3.

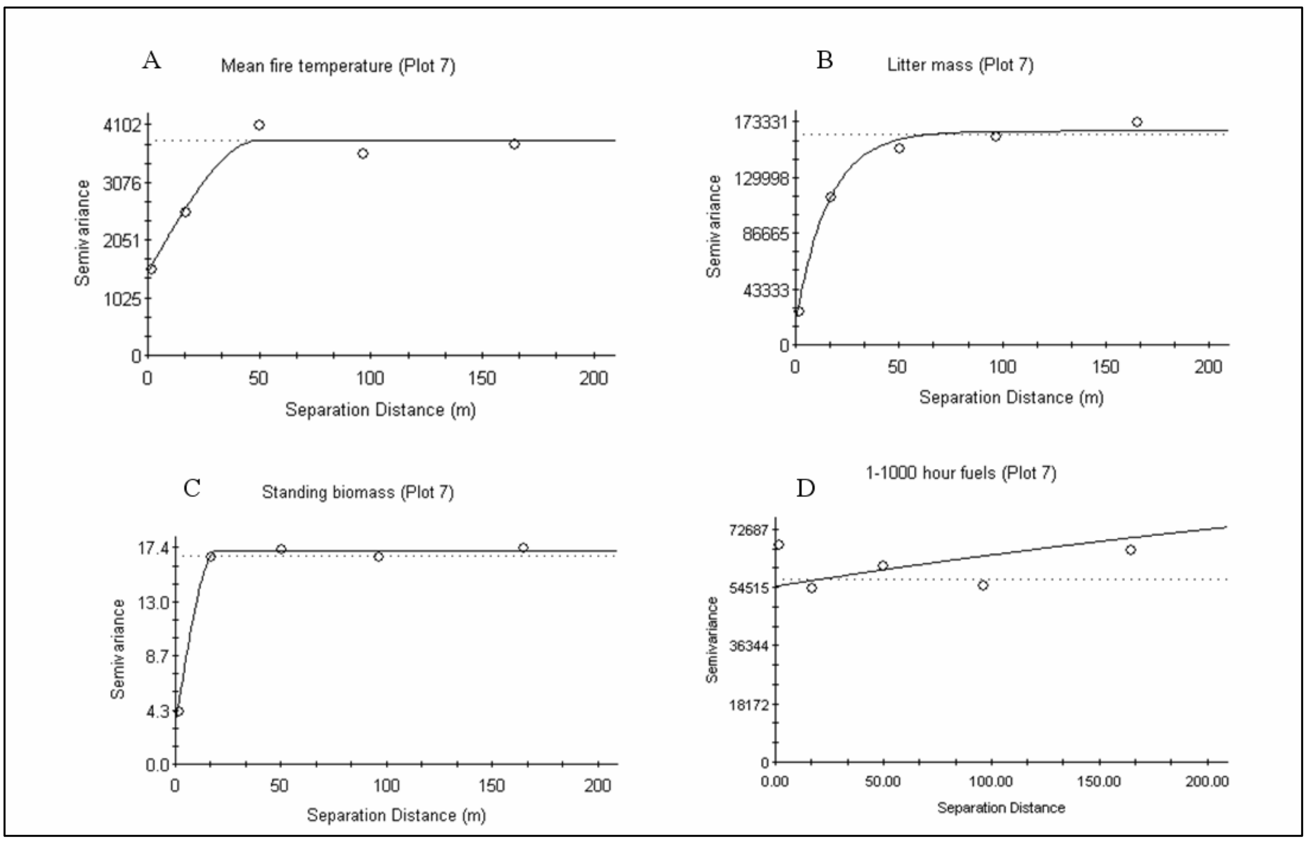


Figure 2. Kriged maps of mean fire temperatures, pre-burn standing biomass, pre-burn 1-1000 hour woody fuels, post-burn litter mass, post-burn standing biomass, and post-burn 1-1000 hour woody fuels in Plot 6 (burn-only treatment), a longleaf pine stand burned in 2002. A kriged map of pre-burn litter mass were not produced because the range of spatial autocorrelation was greater than the scale of the plot. The range of variables represented by the grey scale for Figures 2-5 are reported in Table 4.

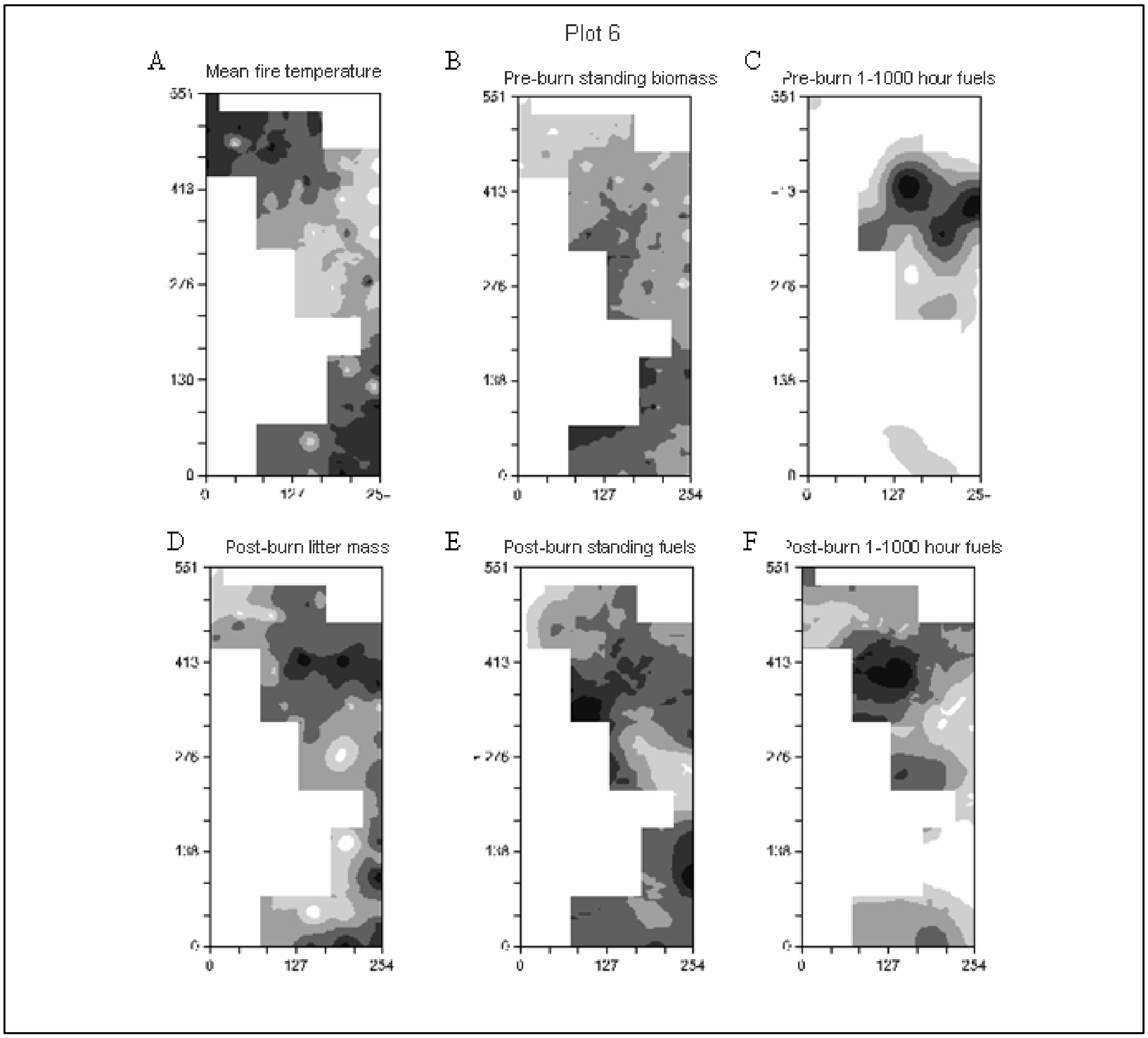


Figure 3. Kriged maps of mean fire temperatures, pre-burn litter mass, and pre-burn 1-1000 hour woody fuels in Plot 4 (herbicide-and-burn treatment), a longleaf pine stand burned in 2003. A kriged map of pre-burn standing biomass was not produced because the range of spatial autocorrelation was greater than the scale of the plot.

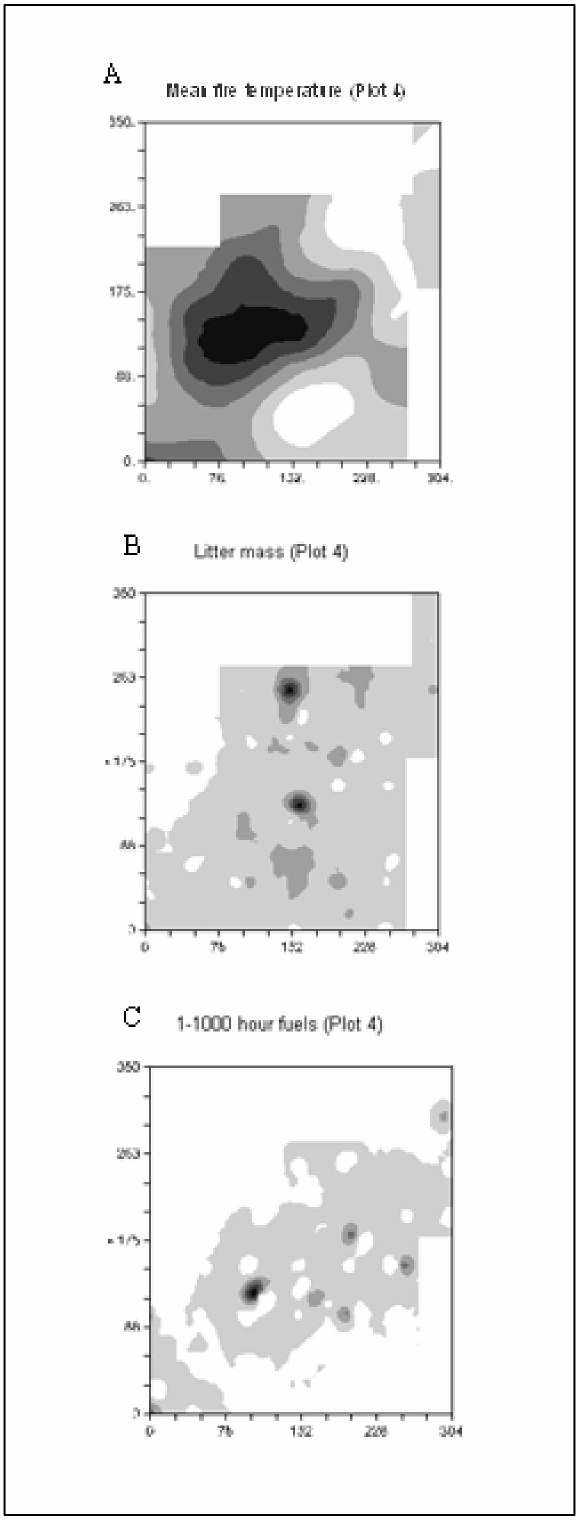
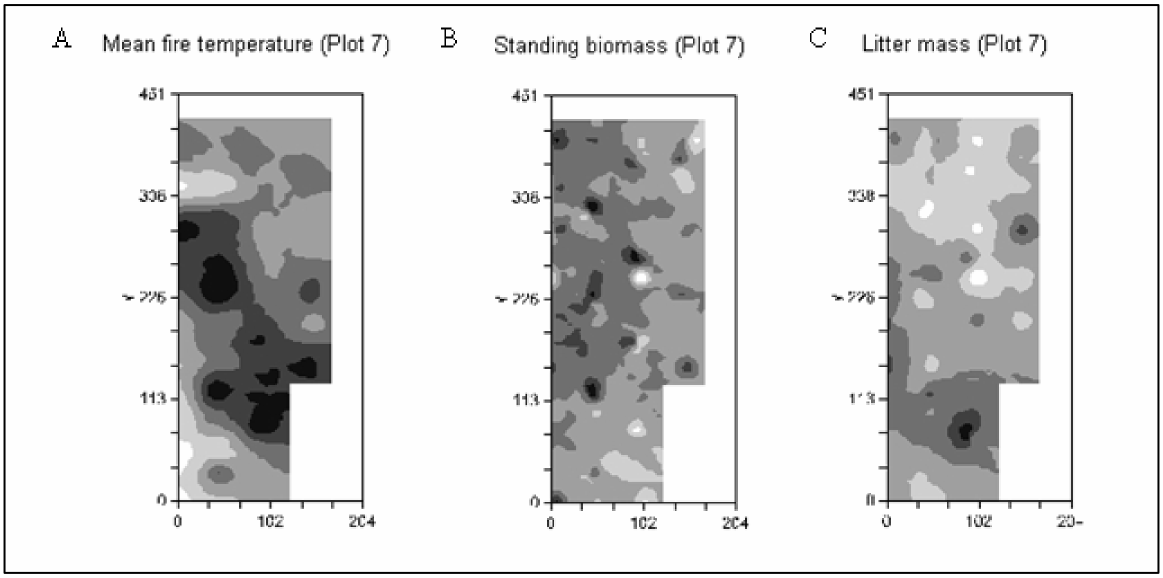


Table 4. Range of variables in Figures 2-5 as indicated by gray scales. The highest value (indicated by black shading) and the lowest value (indicated by white) are given for each variable for which kriged maps were produced.

		Range		
		lowest	**highest**	
Unit	**Variable**	(white)	(black)	units
Burn-only				
Plot 6				
	mean fire temperature	88	278	C
	pre-burn standing biomass	37	179	g m^{-2}
	pre-burn 1-1000 hour fuel mass	315	1838	g m^{-2}
	post-burn standing biomass	59	124	g m^{-2}
	post-burn 1-1000 hour fuel mass	255	890	g m^{-2}
	post-burn litter mass	400	1606	g m^{-2}
Herbicide-and-burn				
Plot 4				
	mean fire temperature	104	254	C
	pre-burn litter mass	713	3642	g m^{-2}
	pre-burn 1-1000 hour fuel mass	48	455	g m^{-2}
Plot 7				
	mean fire temperature	85	232	C
	pre-burn standing biomass	62	147	g m^{-2}
	pre-burn litter mass	502	1775	g m^{-2}
Plot 12				
	mean fire temperature	185	801	C
	pre-burn standing biomass	61	323	g m^{-2}
	pre-burn litter mass	423	1324	g m^{-2}

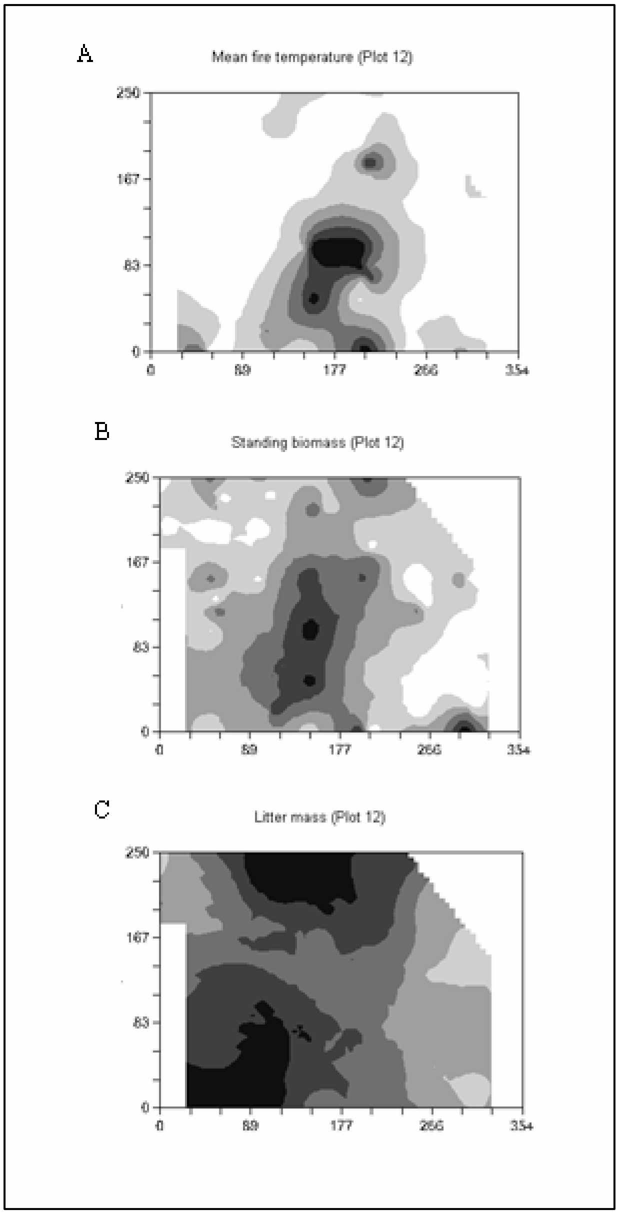
Figure 4. Kriged maps of mean fire temperatures, pre-burn standing biomass, and pre-burn litter mass Plot 7 (herbicide-and-burn treatment), a longleaf pine stand burned in 2003. A kriged map of 1-1000 hour woody fuels was not produced because the range of spatial autocorrelation was greater than the scale of the plot.



Woody fuels revealed the weakest spatial dependence. Semivariograms were calculated for individual dead woody size classes (1, 10, 100 and 1000 hour fuels) however, due the consistently weak patterns found we present results for total down woody mass (sum of the mass of the four size classes). For total down woody mass, only one plot (Plot 4) exhibited strong spatial dependence (94%). Relative structure of the remaining three plots ranged from moderate (65%, Plot 6) to none (0%, Plot 12).

Patterns of pre-burn fuels loads were moderately related to patterns of mean fire temperature, although not consistently in all burns. Plot 12 revealed the closest relationship, with distributions of pre-burn standing fuel mass visually corresponding to patterns of mean fire temperature (Figures 5A and B). In Plot 6, pre-burn standing fuel mass and mean fire temperatures were spatially dependent at similar scales (10 and 27 m) but maps revealed these two variables were related only in the south and eastern portions of that plot (Figures 2A and B). Similarly in Plot 7, both litter and standing fuels varied at similar scales as mean fire temperature (48, 20, 50 m, respectively), but their distributions were similar in only portions of that plot (Figures 4A, B, and C). In Plot 4 (Figures 3A, B, and C), litter and 1-1000 hour fuels had small patch sizes (21 m) while mean fire temperature was spatially dependent at moderate scales (157 m). The weak relationship between pre-burn fuel loads and mean fire temperatures in entire plots or portions of plots were supported by results of a stepwise multiple regression analysis that revealed pre-burn fuel components (mass of standing fuel, litter, and 1-1000 hour fuels) explained only 4% of the variation in mean fire temperature during burns (P = 0.000, df = 395).

Figure 5. Kriged maps of mean fire temperatures, pre-burn standing biomass, and pre-burn litter mass Plot 12 (herbicide-and-burn treatment), a longleaf pine stand burned in 2003. A kriged map of 1-1000 hour woody fuels was not produced because no spatial autocorrelation was detected for this variable.



Spatial patterns of fuel components measured at the end of the growing season following burns in Plot 6 showed moderate relation to those measured pre-burn (Figure 2). For example, standing biomass was high in the southeastern and center sections and low in the northeastern corner of this plot both pre- and post-burn (Figures 2B and E). One-1000 hour fuels also showed some similarities pre- and post-burn (Figures 2C and F). Despite these relationships, the strength and scale of spatial autocorrelation often differed within these fuel components pre- to post-burn. For example, litter mass showed weak spatial autocorrelation prior to burns, but was strongly spatially dependent after burns (Table 3). Standing biomass was strongly spatially dependent before burns, but only moderately so following burns. These inconsistencies may explain why the results of a stepwise multiple regression analysis revealed that pre-burn standing fuel loads and fire temperature indices together explained only 19% of the variation in post-burn standing fuel loads in plot 6 (P = 0.000, df = 98).

DISCUSSION

The results of this study reveal the potential for using semivariance analysis for exploring the scale and strength of spatial patterns in fire behavior. In addition, this study reveals that mean fire temperature during four fires was spatially dependent over medium scales (27-157 m). While several studies have noted fire intensity or temperatures can be highly variable within a single burn (Hobbs et al. 1984, Hobbs and Atkins 1988, Gibson et al. 1990), and that it can vary over relatively small scales (Walley et al. in press, Rice 1993, Fonteyn et al. 1984), using spatial analysis on more than one burn allowed us to see if the scale of variation and strength of spatial dependence is consistent for a particular fuel type under similar burning conditions. Notably, while four of the burns examined revealed some level of spatial dependence, there was considerable variation in both the strength and scale of spatial dependence. For example, variograms suggested that the strength of spatial dependence ("patchiness") was either high (plots six and 12) or moderate (plots four and seven). Patch size, the scale of spatial dependence, was also variable, ranging by a factor of almost six.

These differences are noteworthy given that these burns were conducted in stands with similar topography and fuels types and were burned under similar prescriptions. Even among the three herbicide-and-burn plots (plots four, seven, and 12) the patch size varied by a factor of three. This variation in burn patchiness raises the question: can repeated burns be "replicates" in longleaf pine? These results point to the difficulty of repeatedly achieving similar burn conditions.

However, comparing the variability in these burns to other documented burns suggest more similarities among four fires we examined. For example, studies conducted in xeric shrub systems that have higher intensity stand-replacement fire regimes have noted fire temperatures or intensities varied considerably over finer scales. In Florida scrub for example, Walley et al. (in press) found that pyrometers within 20 cm regularly reported temperatures that differed by more 150^{o} C. By contrast, temperatures at the most closely spaced points (1 m) in our study differed by an average of only 50^{o} C. Both Rice (1993) and Odion and Davis (2000) reported that fire intensity in California chapparal was highly variable over a scale of several meters. The small-scale variation noted by these two studies may reflect the distinctly patchy vegetation cover of both California chaparral and Florida scrub. For example, Rice noted that chaparral communities are strongly influenced by canopy-gap patterns at fine spatial scales (0.1-10 m), leading to periodicities in vegetation at 4-5 m scales. Odion and Davis (2000) reported similar findings for chaparral, with pre-burn canopy cover, soil heating, and post-burn regeneration were patterned in blocks 3-5 m long.

The patch size found in our study overlaps with that found by one other study that examined spatial autocorrelation in fire temperature during low-intensity surface fires. Franklin et al. (1997) found that fire temperatures in upland oak forests were spatially autocorrelated over medium scales (13 to 46 m). These comparisons lend support to the idea that low-intensity surface fires in longleaf pine are patchy over medium scales, as opposed to the finer scales that may be typical of high intensity fires. Therefore, while the fires examined in our study did not have a *narrowly* definable patch size, it may be possible that the patch size of fires can be predicted based on fuel type and stand characteristics over more broadly defined scales (<10 m, 10-200 m, > 200 m). More comparative studies that report spatial autocorrelation are needed to examine this.

Although we expected pre-burn fuel loads to be related to patterns of mean fire temperature, this was not consistently true in all plots. This finding contrasts with results of other studies that have found various measures of fire behavior (fire temperature, burn severity, fire intensity) to be correlated with vegetation and fuel heterogeneity (Hobbs et al. 1984, Hobbs and Atkins 1988, Gibson et al. 1990, Rice 1993, Odion and Davis 2000). It is possible that the combined effects of standing biomass, litter, and 1-1000 hour fuels on fire temperatures prevented us from seeing strong relationships with any single fuel component. For example, overlaying the distribution of standing fuels and litter in Plot 7 would create a similar pattern as mean fire temperature. However, multiple regression analysis confirmed generally weak relationships between pre-burn fuel loads and mean fire temperature, indicating that other variables were likely contributing factors.

The most likely explanation for these inconsistencies is that we did not account for fuel moisture nor measure wind during burns at a scale useful for these spatial analyses. Fuel moisture and wind changes during burns likely introduced additional layers of spatial variation onto the patterns of pre-burn fuel loads. For example, Robichaud and Miller (1999) found that fuel consumption in a Douglas fir/lodgepole pine forest varied according to both pre-burn duff thickness and duff moisture content. Fuel moisture and relative humidity differences may explain why the central section of Plot 6 burned at lower temperatures despite having high loading of 1-1000 hour fuels and standing biomass. This section was located in a moist erosion gully that had a larger hardwood component and was more shaded than the rest of the plot. While measuring fuel moisture across small spatial scales could be easily incorporated into future studies, the costs of developing a technique to measure wind speed and direction (at the time of flaming front passage) at more than 100 spatially referenced points over a landscape scale would be prohibitive.

Large-scale factors such as topography also mask fuel effects on fire behavior (Cheney et al. 1993, Beer 1993, Franklin et al. 1997). For example, Franklin et al. (1997) found that on slopes $<20^{o}$, patterns of fire temperature were more determined by fuel characteristics such as litter/duff biomass. However, on steep slopes (>20^o), fire temperature patch scale was increased to the extent that no relationship was detected between fire temperature and fuels. Slopes at our site were less than 5^o, therefore topography was likely a small factor influencing fire behavior (with the exception of the influence of microtopography on fuel moisture, discussed above).

Another factor that modified patterns in fire behavior was firing technique. Spot application of fire could potentially increase or decrease burn patchiness. Intentionally lighting fuels that would not have burned otherwise could decrease burn patchiness, whereas only lighting areas of high fuel loads might increase patchiness. Spot fires or strips of fires that burn into each other can also create patches of high intensity fire (USDA Forest Service 1989).

Differences in spatial heterogeneity of fires are also thought to be related to overall fire intensity, although studies report different patterns. Hobbs and Atkins (1988) report that more intense fires were less patchy in heath vegetation. Similarly, Gibson et al. (1990) found that areas of more intense fires in Florida sandhill had more homogeneous temperatures. However, Gibson also found that spatial variation was high in both low- and high-intensity fires in tallgrass prairie. It is important to consider scale in interpreting these comparisons. While wildfires or high intensity burns might be homogeneous on small- to intermediate-scales because they are regulated more by large scale factors such as weather conditions; they are likely to create highly distinct patches on a landscape-scale (of burned and unburned areas). For example, Turner et al. (1994) found increased patchiness of fire behavior on a landscape scale under more severe fire conditions during the 1988 Yellowstone Fires. On the other hand, low-intensity and prescribed burns are likely to be heterogeneous on small to intermediate scales because they more apt to respond to small-scale differences in fuel loads, fuel moisture, and microclimate. More research is needed to determine if prescribed fires, conducted under mild weather conditions and systematically ignited, mimic the variability characteristic of more intense wildfires. While fire patchiness of often a stated goal of prescribed burns (e.g., for managing wildlife habitat), the desired scale and degree of burn patchiness is not usually considered. Where burn patchiness is a desirable management goal, managers could incorporate the appropriate spatial heterogeneity in their management burns by manipulating fuel treatments, ignition patterns, or burning conditions.

It is plausible that the larger patch size of the herbicide-and-burn plots than the burn-only plot may be due to a treatment effect, assuming the herbicide treatment increased fuel availability and in turn fire intensity. However, this is unlikely given the generally weak correlation between fuel and fire temperature in these burns. Moreover, there did not appear to be large differences in overall fire temperature between the control and herbicide-and-burn treatments. In any case, more replicates would be needed to verify any treatment effect.

Several studies have noted that spatial variation in fire temperature is important in determining post-fire vegetation characteristics (Hobbs et al. 1984, Hobbs and Atkins 1988, Shafi and Yarranton 1973, Rice 1997, Odion and Davis 2000). This is probably due to the inverse relationship between fire intensity and survivorship of both stems (Dickinson and Johnson 2001) and seeds (Schimmel and Granstrom 1996, Kennard et al. 2002). Therefore, we expected that areas that experience high fire temperatures would result in low fuel accumulation during the following growing season due to stem and seed mortality. While this pattern is evident in some areas of Plot 6, overall there was only a moderate relationship between pre-burn standing fuels (trees, shrubs, grass, forbs, and vines), fire temperature, and post-fire standing fuels. The relatively low range of fire intensity in these burns may have prevented detecting distinct patterns in vegetation following burns. More intense burns, with localized hot spots, might reveal this expected pattern. Research conducted in systems with characteristically high-intensity fires or after severe wildfires has found more evidence of distinct feedback mechanisms between fire and plant communities. For example, both Rice (1993) and Odion and Davis (2000) found that patterns of fire intensity shaped patterns of plant regeneration at similar scales in California chaparral. Research conducted after the 1988 Yellowstone Fires demonstrated the importance of variability in fire intensity, burn size, and burn pattern for generating heterogeneous patterns of pine seedling density, abundance of opportunistic species, and plant diversity (Turner et al.1997) as well as plant mortality, soil heating, ash deposition, and plant and animal dispersal (Christensen et al. 1989). While researchers hypothesize that a fire's affect on the spatial structure of vegetation influences the spatial pattern of future fires (Odion and Davis 2000), our results suggest these feedback links are less robust in systems with low-intensity fire regimes, such as longleaf pine.

CONCLUSIONS AND IMPLICATIONS

Fire temperature during four low-intensity surface fires in longleaf pine forest was spatially dependent and varied significantly over medium scales (27-157 m). Notably, the specific range of this spatial pattern (patch size) was not consistent, even among fires occurring in relatively similar fuel conditions and burned under similar weather conditions. Patterns of pre-burn fuel loads were only moderately related to patterns of mean fire temperature. Incorporating additional fuel parameters (e.g., fuel moisture) and microscale changes in wind and relative humidity may have explained the pattern of fire temperatures more completely. Prescribed burns altered the strength and scale of fuel load spatial patterns from pre- to post-burn. However, the pattern of post-burn fuels loads could not be predicted based on fire temperatures or pre-burn fuel loads alone. The low range of fire temperatures experienced during these low-intensity burns may have prevented detecting distinct patterns in vegetation following burns.

The results of this study and others (Franklin et al. 1997, Rice 1997) that have found spatial autocorrelation in fire temperatures have important research implications. Studies that examine fire effects need to recognize spatial autocorrelation when characterizing fire behavior and account for this variation at appropriate scales. As with any variable that is spatially variable, reporting standard summary statistics (average, max, min, and mode) is less meaningful (Hobbs et al. 1984, Hobbs and Atkins 1988) and may overlook some more important features of fire behavior during a given fire (e.g., patchiness). Studies that do attempt to characterize fire temperature or other indicators of fire behavior must be designed to account for variation at appropriate scales. Autocorrelated variables that are sampled at inappropriate scales can violate assumptions of independence among samples. For researchers examining fire behavior in low-intensity surface fires, samples should be spaced at moderate scales (this study suggests 30 to >150 m) to be independent. This indicates that studies that record fire temperatures using conventional data loggers (with multiple thermocouple arrays) may be reporting temperatures within single patches. If the goal is to characterize fire behavior over large treatment units, using single thermocouples at widely spaced intervals to ensure that samples are independent would optimize sampling effort.

Spatial autocorrelation in fire behavior also has important implications for management. Burn patchiness is often a stated goal of management burns. Spatial analysis provides a useful way to quantify this characteristic and can help to elucidate what scale and strength of patchiness is desirable for different community types and different management goals. For example, do prescribed fires, conducted under optimum weather conditions and systematically ignited, mimic the variability characteristic of natural fires? Managers could incorporate the appropriate spatial heterogeneity in their management burns by manipulating fuel treatments, ignition patterns, or burning conditions. More studies of fire patchiness and its controls should be conducted in other fuel types, comparing different firing techniques (e.g., back vs. head fires), and under different burning conditions (prescribed fires vs. wildfires).

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