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forest management

Fuel and Vegetation Trends after Wildfire in Treated versus Untreated Forests

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Increasing size and severity of wildfires have led to increased interest in managing forests for resiliency to future disturbances. Comparing and contrasting treated versus untreated stands through multiple growing seasons postfire provide an opportunity to understand processes driving responses and can guide management decisions regarding resiliency. In treated and untreated forests, we compared fire effects 2–10 growing seasons following fire on 3 different fires in New Mexico and Arizona. We estimated understory cover, standing crop, fuel loading, and basal area in (1) lop, pile, burn; (2) lop and scatter; (3) harvest and burn; and (4) untreated control stands. Untreated sites had persistent bare soil exposure and less litter cover up to 10 growing seasons after fire. However, there were few differences in standing crop among years and treatments. Falling rampikes contributed to greater coarse woody debris on untreated sites versus treated sites 6–10 years postfire. However, there were few differences in fine fuel loading among treatments. Proactive management using the full range of silvicultural tools can reduce fire severity and create desired stand conditions, depending on management objectives.

Keywords: conifer mortality, fire effects, forest management, resiliency, understory response

Western forest managers face a landscape characterized by an ever-increasing area on which they must make postfire management decisions (Miller et al. 2012). Between 2003 and 2012, 80,000+ fires burned ~5.6 million ha on US Department of Agriculture (USDA) Forest Service lands (National Interagency Fire Center).[1] Further, over the last four decades, the number of ha burned at high fire severity have increased (Miller et al. 2009, Miller and Safford 2012, Miller et al. 2012). The 2011 Las Conchas Fire in New Mexico provides one example: 18,000 ha burned predominantly at high and moderate severities in the first 13 hours. Given the number of similar scenarios across the western landscape, as well as predictions for warmer and drier climates (Diffenbaugh et al. 2008), interest in managing forests for resiliency to future disturbances such as insects, disease, and fire is increasing (Stevens-Rumann et al. 2012).

Managers want to foster resilient landscapes using silvicultural treatments. Understanding how ecosystems respond in treated and untreated stands through multiple growing seasons following fire (GSF) will help managers make decisions aimed to foster resiliency. Specific management questions include the following: How will understory vegetation, fuel loads, and stand structure respond immediately following fire (i.e., first-order fire effects) as well as in the months and years after fire (e.g., second-order fire effects) depending on fire severity. We focused on the latter with a particular interest in comparing treated versus untreated ecosystem responses following fire through multiple growing seasons.

There is a considerable body of scientific literature available on how southwestern forests respond to fire (e.g., Pearson et al. 1972, Ffolliott et al. 1977, Lowe et al. 1978, Foxx 1996, Crawford et al. 2001, Laughlin et al. 2004, Huisinga et al. 2005, Bataineh et al. 2006, Abella and Fulé 2008, Haire and McGarigal 2010, Roccaforte et al. 2012). However, none of the above-listed studies had any prefire treatments, and they only looked at high fire severity (Bataineh et al. 2006 notwithstanding). Conversely, there is little information comparing overstory and understory responses following fire between treated versus untreated sites (Griffis et al. 2001, Shive et al.

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; kilograms (kg): 1 kg = 2.2 lb; milligrams (mg): 1 mg = 0.015 gram; hectares (ha): 1 ha = 2.47 ac.

2013, Stevens-Rumann et al. 2013, Stevens et al. 2014). Further, none of these studies offered temporal analyses.

We examined under- and overstory structure and fuel loads following wildfire in treated versus untreated stands in New Mexico and Arizona. Three replicated study sites were analyzed and reported individually because of their unique treatments, forest types, or years since fire. Prefire management treatments included noncommercial lop, pile, burn (LPB); noncommercial lop and scatter (L&S); and commercial harvest followed by prescribed burn (H&B). Our objectives were to quantify second-order fire effects, compare them in treated versus untreated stands, and identify potential emerging issues.

Methods

Study Area

The study areas were located within the 2002 Rodeo-Chediski wildfire on the Apache-Sitgreaves National Forest in Arizona and the 1998 Oso and 2002 Borrego wildfires in the Santa Fe National Forest, New Mexico. Study sites within the Rodeo-Chediski fire were lower (2015 m) montane coniferous stands composed of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and Gambel oak (*Quercus gambelii* Nutt.). Study sites were characterized by little to no slope (i.e., $\leq$5%). Intensity was estimated to be 1,732+, 998, and 485 kJ m^{-1} s^{-1} for untreated, L&S, and LPB study sites (Cram et al. 2006). Postfire restoration treatments included aerial seeding on L&S and untreated stands only. Grazing on study sites was suspended 4 years following wildfire.

The Borrego and Oso fires burned in upper (2,573 m) montane coniferous stands composed of ponderosa pine with some Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and white fir (*Abies concolor* [Gord. & Glend.] Hildebr.). Borrego sites were characterized by northeast and west aspects with slopes less than 10%, whereas Oso sites were characterized by little to no slope. Borrego intensity was estimated to be 1,833 and 405 kJ m^{-1} s^{-1} for untreated and harvest and burn study sites (Cram et al. 2006). Oso intensity was estimated to be 2,030 and 184 kJ m^{-1} s^{-1} for untreated and harvest and burn study sites (Cram et al. 2006). No postfire restoration treatments were conducted on these study sites. Grazing at light to conservative stocking rates was not deferred on our study sites following either fire.

Coniferous study sites within the Rodeo-Chediski fire were more xeric than New Mexico study sites. Mean annual precipitation (rainfall only) between 1993 and 2007 for the study sites was as follows: Rodeo-Chediski, 39 cm; Borrego, 41 cm; and Oso, 44 cm (Western Regional Climate Center 2008). During the summer months, precipitation in the form of high-intensity, short-duration afternoon thundershowers is common to the study areas.

Study Design

We used the same study sites as Cram et al. 2006. They selected study sites from 11 national forests in Region 3 (New Mexico and Arizona) suitable for comparing wildland fire behavior between treated and untreated forest stands. Study sites were adjacent, silviculturally treated and untreated forest stands that had similar slope and aspect properties.

Replicated study stands, defined entirely by management treatment within wildfire boundaries, were >16 ha. Specific stand treatment history and silvicultural prescription were researched and verified by consulting with the prescription forester (Table 1). Rodeo-Chediski treatments were characterized as noncommercial fuel reductions. The silvicultural prescriptions for the Borrego and Oso study sites were commercial and designed similar to restoration treatments in terms of residual stand structure and fire reintroduction (Bill Armstrong, USDA Forest Service, pers. comm., June 2, 2003). The Rodeo-Chediski study site had 3 replications of 3 treatments: (1) noncommercial LPB; (2) noncommercial L&S; and (3) untreated control (n = 9 stands). The Borrego study site had 3 replications of 2 treatments: H&B and untreated control (n = 6 stands). The Oso study site had 2 replications of 2 treatments: H&B and untreated control (n = 4 stands).

Table 1. Study site characteristics in Arizona and New Mexico.

Study site	Treatment year	Basal area (m^2 ha^{-1})
Lower montane (2002 Rodeo-Chediski fire)		
LPB	1998–1999	14.8 ± 2.7
L&S	1998–1999	17.5 ± 4.1
UT	NA	25.2 ± 2.9
Upper montane (2002 Borrego fire)		
H&B	1994–1997	13.7 ± 0.7
UT	NA	22.0 ± 2.9
Upper montane (1998 Oso fire)		
H&B	1994–1995	11.8 ± 0.8
UT	NA	25.3 ± 1.0

H&B, commercial harvest followed by prescribed burn; L&S, noncommercial lop and scatter; LPB, noncommercial lop, pile, burn; UT, untreated; NA, not applicable. Data are presented as means ± SE.

Vegetation and Fuel Sampling

Two permanent 100-m transects to measure understory structure were randomly located within each experimental unit. To characterize understory structure, we estimated percent cover in 10 1-m^2 plots per transect in the following categories: grasslike, forb, woody (0–1 and >1–2 m height classes), litter, rock, live stem, dead stem, and bare soil. Percent cover for each category was estimated using a cover value scale following Brown et al. (1982). Dead and down fuel loading (kg ha^{-1}) was estimated 3 times per transect following Brown et al. (1982). Grass and forb herbaceous fuel loading (kg ha^{-1}) was estimated 5 times per transect in 0.3 × 0.6-m plots. To avoid clipping the same plot in subsequent years, a systematic protocol was developed. Herbaceous material was clipped at surface level, dried at 60° C for 48 hours, and weighed. To avoid bias from surrounding stands and an edge effect, no sampling was conducted within 50 m of stand edge (Mueller-Dombois and Ellenberg 1974, p. 123). All data were collected postfire in the fall of 2003–2007. All cover estimates were done by the same individual except for estimates taken on the Borrego site in 2005. Data were not collected on one untreated replicate on the Borrego site in 2005 due to an ongoing firewood sale.

To characterize overstory stand conditions, we estimated basal area (m^2 ha^{-1}) and dbh (1.37 m) and recorded live/dead status within five randomly located variable-radius plots per treatment. In subsequent years, repeat measurements were taken at same plots. Variable-radius plots were determined by using a 10-factor prism. Basal area was calculated following Avery and Burkhart (1994).

We followed fire terminology as suggested and defined by Keeley (2009) as it related to fire severity, burn severity, and ecosystem responses—our primary interest. Ecosystem responses, also known

Table 2. Five year (2003–2007) understory cover response in treated and untreated forest stands in New Mexico and Arizona, USA, reported by GSF.

		Understory cover response at site with treatment							
		Lower montane			Upper montane			Upper montane	
Variable	GSF	LPB	L&S	UT	H&B	UT	GSF	H&B	UT
		(%)						(%)	
Grass	2	2.9 ± 4.5	4.1 ± 4.5b	5.3 ± 4.5c	10.7c ± 2.6	5.9b ± 2.6	6	25.7 ± 5.8A	6.1 ± 5.8B
	3	5.6	14.8a	16.3b	16.2bc	15.9a	7	43.9A	7.3B
	4	10.2	21.4a	25.6a	12.9c	13.8 ± 3.2ab	8	50.3A	13.1B
	5	11.9	24.5a	14.6bc	24.1a	17.7a	9	55.5A	17.8B
	6	15.1	19.4a	9.2bc	22.0ab	15.3a	10	52.4A	21.2B
Forb	2	3.0 ± 4.0c	9.6 ± 4.0b	5.8 ± 4.0c	6.9 ± 1.5b	2.7 ± 1.5c	6	8.4 ± 1.9b	5.8 ± 1.9c
	3	9.1bc	15.1b	16.6b	11.1ab	10.3b	7	12.4ab	7.3c
	4	18.9a	24.0a	20.7ab	9.2b	7.1 ± 2.1bc	8	15.3a	12.3ab
	5	15.9ab	18.5ab	23.2ab	11.7ab	12.5ab	9	16.1a	11.9bc
	6	16.9ab	26.4a	28.9a	15.3a	17.4a	10	18.5a	16.7a
Woody 0–1 m	2	4.0 ± 1.5bc	4.8 ± 1.5ab	1.1b ± 1.5	11.7 ± 2.8	5.0 ± 2.8	6	5.7 ± 1.9	9.6 ± 1.9
	3	2.2c	3.0b	4.3b	14.2	7.6	7	8.8B	20.0A
	4	7.0ab	4.5ab	4.6b	14.7	10.4 ± 3.7	8	7.3B	17.0A
	5	11.1a	8.3a	10.2a	14.0	14.3	9	4.8B	22.9A
	6	7.8ab	6.4ab	9.3a	21.9	11.6	10	8.5	15.1
Woody 1–2 m	2	0.5 ± 1.2b	0.1 ± 1.2ab	0.0 ± 1.2b	0.5 ± 2.3	0.7 ± 2.3	6	0.0 ± 2.3	3.4 ± 2.3
	3	0.2b	0.1b	2.1ab	2.5	0.0	7	1.1	4.8
	4	3.0ab	0.4b	2.0ab	2.5	0.8 ± 4.0	8	1.4	6.3
	5	5.1a	3.6a	3.8a	4.0	4.0	9	2.2B	13.5A
	6	2.3ab	2.6ab	3.4ab	11.8	5.3	10	2.1B	11.4A
Litter	2	45.5 ± 4.3Ab	37.5Aab ± 4.3	5.8 ± 4.3B	34.6 ± 6.8Abc	8.3 ± 6.8Bbc	6	55.2 ± 3.3Aa	16.5 ± 3.3B
	3	58.2Aa	45.2Ba	9.0C	36.7Abc	14.1Bab	7	45.4Aa	19.3B
	4	43.2Ab	21.4Bc	6.0C	32.8Ac	4.4Bc ± 7.3	8	23.9b	21.7
	5	42.4Ab	25.0Bbc	13.1B	48.7Aab	25.1Ba	9	25.3b	26.2
	6	35.7Ab	24.4ABc	14.1B	54.2Aa	18.9Bab	10	28.1b	22.1
Soil	2	51.6 ± 5.8Ba	50.1 ± 5.8Ba	79.0 ± 5.8Aa	41.3 ± 5.7Ba	81.4 ± 5.7Aa	6	9.6 ± 1.9Ba	34.9 ± 1.9Ab
	3	25.3Bb	26.2Bb	56.2Ab	14.4Bb	52.6Ab	7	15.5Ba	45.9Aa
	4	21.6b	21.5b	35.5c	20.3Bb	46.6 ± 6.2Ab	8	5.4Bb	23.3Ac
	5	12.2b	14.6b	26.8c	16.6Bb	42.9Ab	9	4.7Bb	14.3Ad
	6	22.1b	23.6b	33.0c	15.5Bb	41.2Ab	10	4.8Bb	17.9Acd

Data are means ± SE. Within site, row means followed by the same uppercase letters or without letters were not significantly different at the 0.05 level (least significant difference test). Within site, column means followed by the same lowercase letters or without letters were not significantly difference at the 0.05 level (least significant difference test). Means are averages of class midpoints and therefore will not total 100%. Reported SEs are experiment-wise model estimates used for making inferences. Treatment codes shown in Table 1.

as second-order fire effects, are functional processes that are altered by fire such as regeneration, recolonization by plants, and fuel load dynamics.

Data Analysis

Because of differences in treatments pre- and postfire, forest cover types, and years since fire, data were analyzed and reported separately for each site. Hereafter, Rodeo-Chediski sites are referenced as lower montane study sites. Taking advantage of a unique circumstance, results from the Borrego and Oso study sites were juxtaposed in reporting due to their chronosequence nature in regard to years since fire. Specifically, Borrego data were collected 2–6 GSF and Oso data was collected 6–10 GSF. Hereafter, the Borrego and Oso sites are referenced as upper montane study sites 2–6 and 6–10 GSF. Annual data were collected from 2003–2007.

We used proc mixed in SAS software, version 9.1 (SAS Institute, Inc. 2008). Fixed effects in the model were year, treatment, and year × treatment interaction. Because data were collected in multiple years on the same plots, we used year as a repeated factor in the model. To account for correlation between repeated measures of the same plots, experimental units within treatments were used as random effects. Variance was modeled as being homogeneous within sites among treatments. We used linear mixed models to determine differences within sites among treatments (cross-sectional) and years (longitudinal) in response variables. Reported means for dependent variables were summarized by site, treatment, and number of GSF. To reduce the risk of making one or more type I errors with multiple comparisons between means, we used the F-protected least significant difference test with $P = 0.050$ (Steel et al. 1997, p. 178).

Results

Understory Cover and Standing Crop

Year Comparisons

Lower montane untreated sites decreased in mean bare soil 2–4 GSF; bare soil thereafter was maintained through 6 GSF (mean = 32% ± 5 SD) (Table 2; Figure 1). Nonetheless, bare soil was the dominant cover category 2–6 GSF in untreated sites compared among all cover categories. Bare soil on L&S and LPB sites decreased 3 GSF and remained unchanged through 6 GSF (mean = 22% ± 5 SD; mean = 20% ± 6 SD). Bare soil on upper montane untreated sites decreased 3 GSF and remained unchanged 4–6 GSF (mean = 45% ± 5 SD) before generally decreasing 6–10 GSF (mean = 27% ± 13 SD). Similar to lower montane sites, bare soil was the dominant cover category in untreated upper montane sites

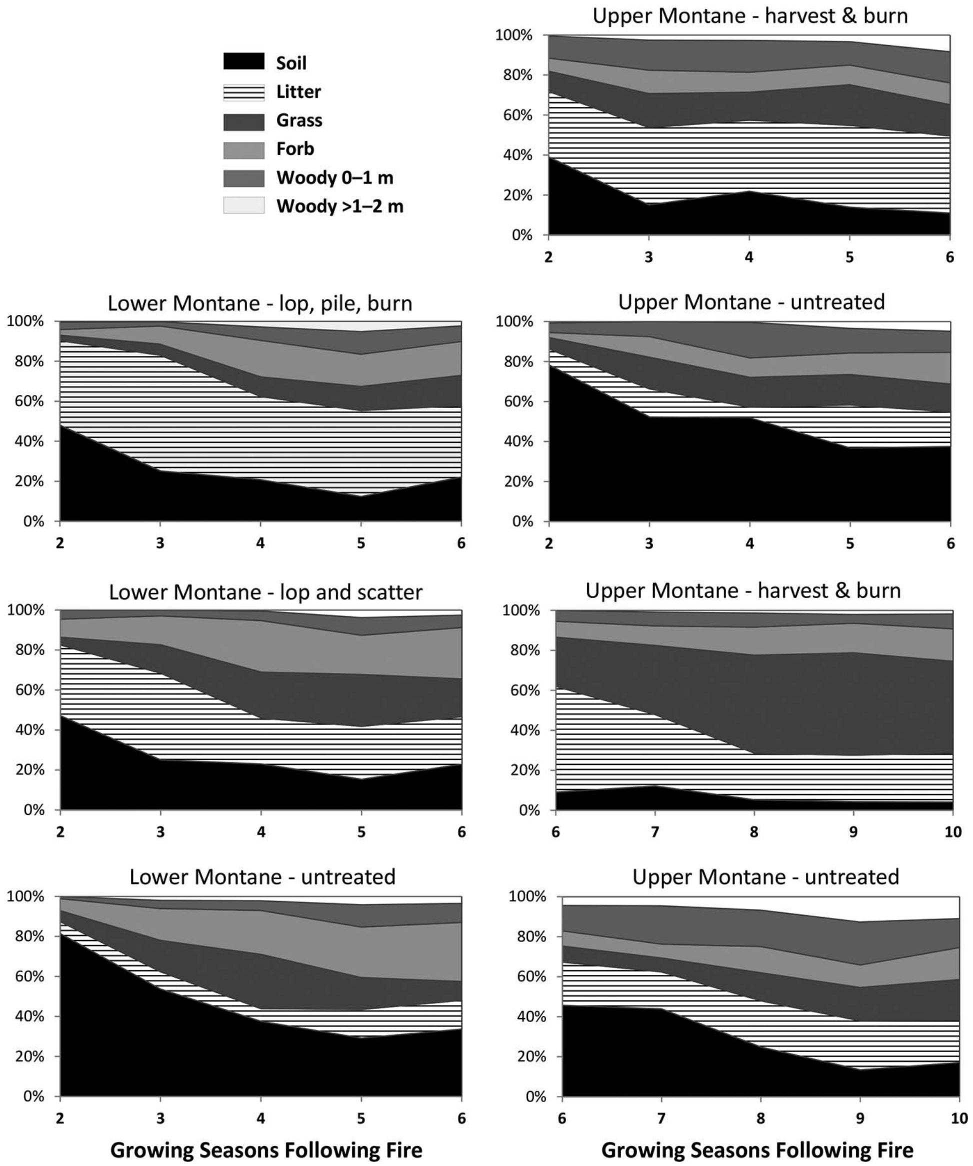

Figure 1. Five-year (2003–2007) distribution of understory cover response on treated and untreated study sites in New Mexico and Arizona, USA, reported by GSF. Lower montane treatments included noncommercial LPB and noncommercial L&S; upper montane treatments included H&B.

compared among all cover categories 2–6 GSF. Bare soil on H&B sites decreased 3 GSF and then remained unchanged 4–6 and 6–10 GSF (mean = 17% ± 3 SD; mean = 8% ± 5 SD).

Mean litter cover on lower montane untreated sites did not change 2–6 GSF (mean = 10% ± 4 SD) (Table 2; Figure 1). Likewise, litter cover on LPB sites essentially remained unchanged 2–6 GSF with a 1-year increase 3 GSF (mean = 42% ± 4 SD). Litter cover was the dominant cover category 3–6 GSF in LPB sites compared among all cover categories. Litter cover on L&S sites decreased 4 GSF. Litter cover on untreated upper montane sites generally increased 2–6 GSF and then remained unchanged 6–10 GSF. Litter cover on H&B sites slightly increased 2–6 GSF and then decreased 8 GSF. On upper montane sites, litter was the greatest cover component on H&B sites 3–6 GSF.

Mean grass cover on lower montane untreated sites increased 2–4 GSF, decreased 5 GSF, and then remained unchanged 6 GSF (Table 2; Figure 1). Grass cover on L&S sites increased 3 GSF and then remained unchanged through 6 GSF. Grass cover on LPB sites remained unchanged 2–6 GSF (mean = 9% ± 5 SD). On upper montane sites, grass cover on untreated sites remained generally unchanged 2–6 and 6–10 GSF (mean = 14% ± 5 SD; mean = 13% ± 7 SD). Grass cover on H&B sites generally increased 2–6 GSF and then remained unchanged 6–10 GSF. Mean forb cover on lower and upper montane sites generally increased 2–6 and 6–10 GSF regardless of treatment. Mean woody cover 0–1 m and >1–2 m (i.e., predominantly *Quercus* spp.) generally increased across all lower montane sites 2–6 GSF. In contrast, there was no change in woody cover on upper montane sites between years. Generally, there were no differences between years in mean grass or forb standing crop (kg ha^{-1}) after fire on lower or upper montane sites (Table 3).

Treatment Comparisons

Bare soil on lower montane untreated sites was greater 2–3 GSF than on LPB and L&S sites (Table 2; Figure 1). However, there were no differences in bare soil 4–6 GSF. On upper montane sites, bare soil was greater on untreated sites 2–6 and 6–10 GSF than on H&B

Table 3. Five year (2003–2007) fuel loading and standing crop response in treated and untreated study sites in New Mexico and Arizona, USA, reported by GSF.

		Fuel loading and standing crop at site with treatment							
		Lower montane			Upper montane			Upper montane	
Variable	GSF	LPB	L&S	UT	H&B	UT	GSF	H&B	UT
		t ha^{-1}						t ha^{-1}	
1 hour	2	0.04 ± 0.03	0.02 ± 0.03c	0.01 ± 0.03d	0.03 ± 0.01	0.01 ± 0.01b	6	0.19 ± 0.03a	0.17 ± 0.03
	3	0.05	0.07bc	0.06cd	0.01	0.03b	7	0.05b	0.20
	4	0.05	0.09abc	0.14ab	0.02	0.02b ± 0.02	8	0.05b	0.13
	5	0.11	0.11ab	0.11bc	0.05B	0.13Aa	9	0.02b	0.08
	6	0.10	0.16a	0.20a	0.07B	0.17Aa	10	0.08b	0.10
10 hour	2	0.55 ± 0.22ab	0.38 ± 0.22c	0.0 ± 0.22c	0.80 ± 0.65	0.21 ± 0.65	6	0.78 ± 0.28	1.61b ± 0.28
	3	0.17b	0.45c	0.28c	0.66	2.04	7	0.62B	3.11Aa
	4	0.42b	0.42c	0.80b	0.73	0.77 ± 0.93	8	0.62	1.25b
	5	0.55ab	1.04b	1.11b	0.87	1.52	9	0.26	0.88b
	6	0.97a	1.63a	2.60a	0.52	2.22	10	0.94	0.99b
100 hour	2	0.55 ± 0.61	0.41 ± 0.61c	0.14 ± 0.61d	1.79 ± 1.14	0.14 ± 1.14	6	1.65 ± 1.54	4.13
	3	1.10	0.55c	0.69cd	1.79	2.48	7	1.03	3.93
	4	1.38	1.38c	2.07c	1.65	2.22 ± 2.22	8	2.48	3.31
	5	2.21	3.03b	3.58b	1.65	1.14	9	2.69	6.20
	6	1.65C	4.82Ba	9.10Aa	2.07	1.14	10	2.69	4.96
1,000 hour	2	1.69 ± 2.84	1.26 ± 2.84c	0.65 ± 2.84c	7.44 ± 3.70	0.09 ± 3.70c	6	1.24 ± 4.88B	36.88 ± 4.88A
	3	0.79	1.05c	0.16c	5.45	3.70c	7	0.69B	25.74A
	4	4.59	10.32b	4.61bc	9.81	7.67 ± 4.17bc	8	0.67B	29.51A
	5	7.60B	24.18Aa	11.48Bab	8.70	11.18ab	9	4.78B	26.60A
	6	7.38B	17.26Aab	17.77Aa	4.07	16.28a	10	3.09B	26.29A
Grass standing crop	2	0.09 ± 0.10	0.16 ± 0.10	0.16 ± 0.10	0.24 ± 0.04	0.08 ± 0.04	6	0.37 ± 0.12b	0.12 ± 0.12
	3	0.06	0.32	0.35	0.15	0.21	7	0.21b	0.15
	4	0.16B	0.47A	0.35AB	0.38	0.37 ± 0.06	8	0.27b	0.20
	5	0.10B	0.49A	0.21AB	0.19	0.12	9	0.29b	0.10
	6	0.25	0.43	0.21	0.32	0.32	10	0.85a	0.56
Forb standing crop	2	0.13 ± 0.12	0.36 ± 0.12	0.10 ± 0.12	0.19 ± 0.04a	0.12 ± 0.04	6	0.20 ± 0.04	0.17 ± 0.04
	3	0.09	0.31	0.35	0.14a	0.12	7	0.13	0.10
	4	0.38	0.42	0.59	0.13ab	0.11 ± 0.07	8	0.17	0.14
	5	0.29	0.29	0.29	0.05b	0.11	9	0.20	0.06
	6	0.36	0.65	0.50	0.20a	0.34	10	0.40	0.36

Data are means ± SE. Within site, row means followed by the same uppercase letters or without letters were not significantly different at the 0.05 level (least significant difference test). Within site, column means followed by the same lowercase letters or without letters were not significantly different at the 0.05 level (least significant difference test). Reported SEs are experiment-wise model estimates used for making inferences. Treatment codes are shown in Table 1.

sites. Litter cover on lower montane LPB sites was greater than on untreated sites 2–6 GSF. On upper montane sites, litter cover was greater on H&B sites than on untreated sites 2–6 and 6–7 GSF. Thereafter, there was no difference 8–10 GSF.

There was no difference in grass, forb, woody cover 0–1 m, or woody cover >1–2 m among treatments regardless of GSF on lower montane sites (Table 2; Figure 1). However, on upper montane sites, grass cover on LPB sites was greater than on untreated sites 6–10 GSF. Woody cover 0–1 m on untreated montane sites was greater than on H&B sites 7–9 GSF, whereas woody cover >1–2 m was greater than on H&B sites 9–10 GSF. Generally, there were no differences in standing crop among treatments regardless of study site or GSF (Table 3) with the exception of L&S sites 4–5 GSF.

Fuel Loading

Year Comparisons

Lower montane mean 1,000-hour fuel loads increased 4 and 5 GSF on L&S and untreated sites, whereas there was no change on LPB sites 2–6 GSF (Table 3; Figure 2). Upper montane 1,000-hour fuels also increased on untreated sites 5 GSF, but then remained unchanged 6–10 GSF. Upper montane 1,000-hour fuel loads on H&B sites did not change 2–6 or 6–10 GSF.

Lower montane mean 100-hour fuel loads increased 4 and 5 GSF on untreated and L&S sites, whereas there was no change on LPB sites 2–6 GSF (Table 3; Figure 2). Upper montane 100-hour fuel loads did not increase on untreated or H&B sites 2–6 or 6–10 GSF. Lower montane mean 10-hour fuel loads increased 4–6 and 5–6 GSF on untreated and L&S sites. Lower montane 10-hour fuel loads on LPB sites did not change appreciably 2–6 GSF. Upper montane 10-hour fuels did not change 2–6 or 6–10 GSF on untreated or H&B sites. Lower montane mean 1-hour fuel loads increased 4 GSF on untreated sites, whereas there was no change 2–6 GSF on LPB sites. Upper montane 1-hour fuel loads increased 5 GSF on untreated sites, but then remained unchanged 6–10 GSF. Upper montane H&B 1-hour fuel loads decreased 7 years after fire.

Treatment Comparisons

There were no differences in 1,000-hour fuels among treatments on lower montane sites 2–4 GSF (Table 3; Figure 2). However, 5 and 6 GSF, 1,000-hour fuels on L&S and untreated sites were greater than on LPB sites. There was no difference in 1,000-hour fuels between treatments on upper montane sites 2–6 GSF. However, untreated sites had greater 1,000-hour fuels than H&B sites 6–10 GSF.

There were no differences among treatments in lower montane 100-hour fuels 2–5 GSF (Table 3; Figure 2). However, 6 GSF,

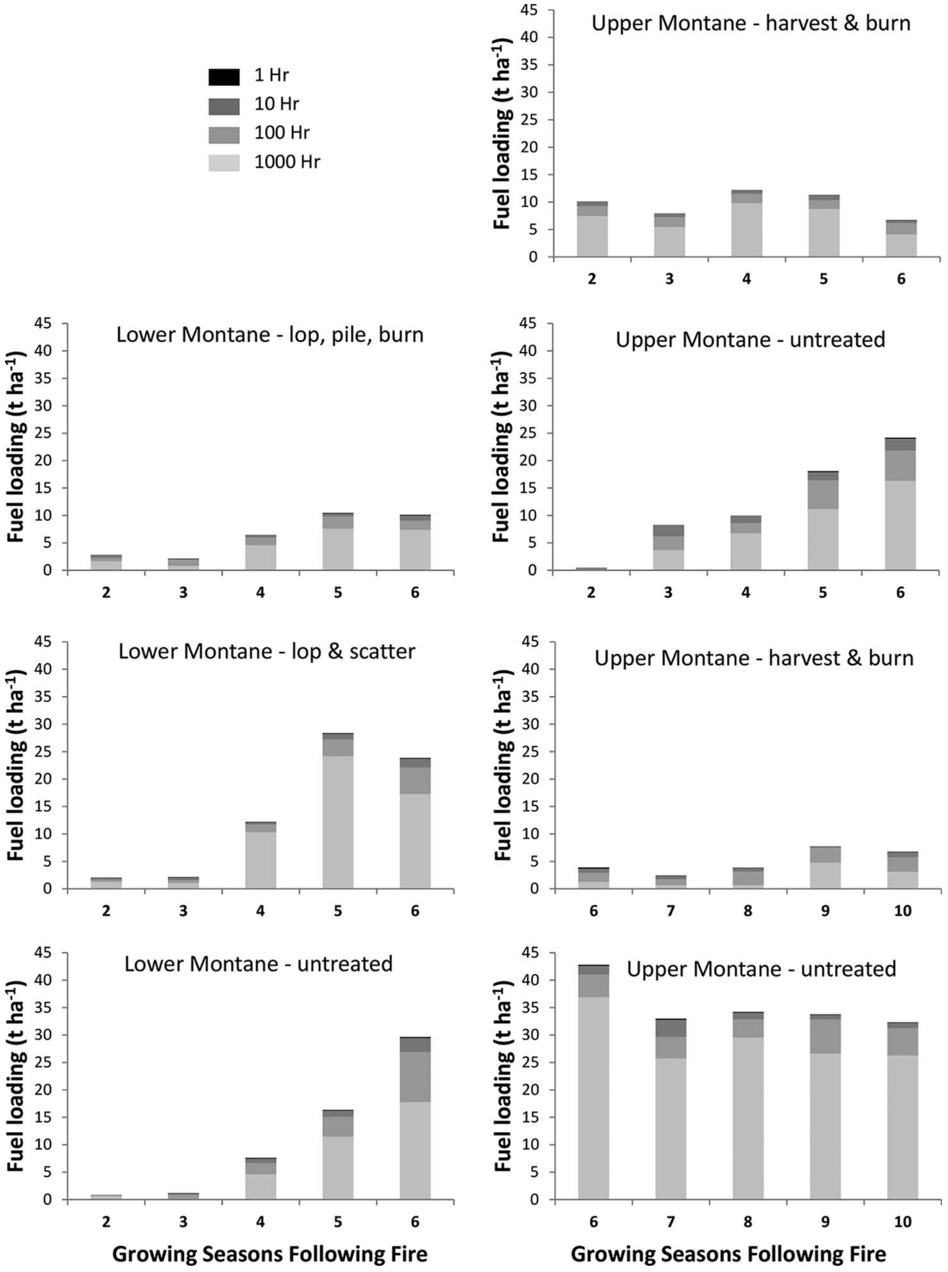

Figure 2. Five year (2003–2007) fuel loading (Mg ha^{-1}) response on treated and untreated study sites in New Mexico and Arizona, USA, reported by GSF. Lower montane treatments included noncommercial LPB and noncommercial L&S; upper montane treatments included H&B.

untreated and L&S sites had greater 100-hour fuels than LPB sites. There were no differences in 100-hour fuels between upper montane treatments 2–6 and 6–10 GSF. There were no differences in 10-hour fuels across all the sites and treatments. There were no differences in 1-hour fuels among treatments on lower montane sites 2–6 GSF. On upper montane sites, 1-hour fuels were greater on untreated sites 5–6 GSF than on H&B sites. No differences in 1-hour fuels were recorded 6–10 GSF between untreated and H&B sites.

Overstory

Year Comparisons

There was no difference in live basal area or annual mortality rate between years on lower montane LPB sites and upper montane H&B sites (Figure 3). Cumulative mean tree mortality on lower montane LPB sites was 9% ± 7 SD. Cumulative mean tree mortality of upper montane H&B sites was 5% ± 4 and 4% ± 4 SD 2–6 and 6–10 GSF. Cumulative mean basal area on lower montane LPB sites was 9 ± 1 m^2 ha^{-1} 2–6 GSF. Cumulative mean basal area on upper montane H&B sites was 12 ± 0.4 and 10 ± 0.4 m^2 ha^{-1} 2–6 and 6–10 GSF.

Treatment Comparisons

Tree mortality on LPB and H&B sites was negligible compared with that on untreated sites. Tree mortality on untreated sites was 100% following crown fire on lower and upper montane sites (Bill Armstrong, USDA Forest Service, pers. comm., June 2, 2003, regarding mortality on Oso sites immediately following the 1998 fire). Tree mortality on L&S sites was also 100%, but overstory was 100%

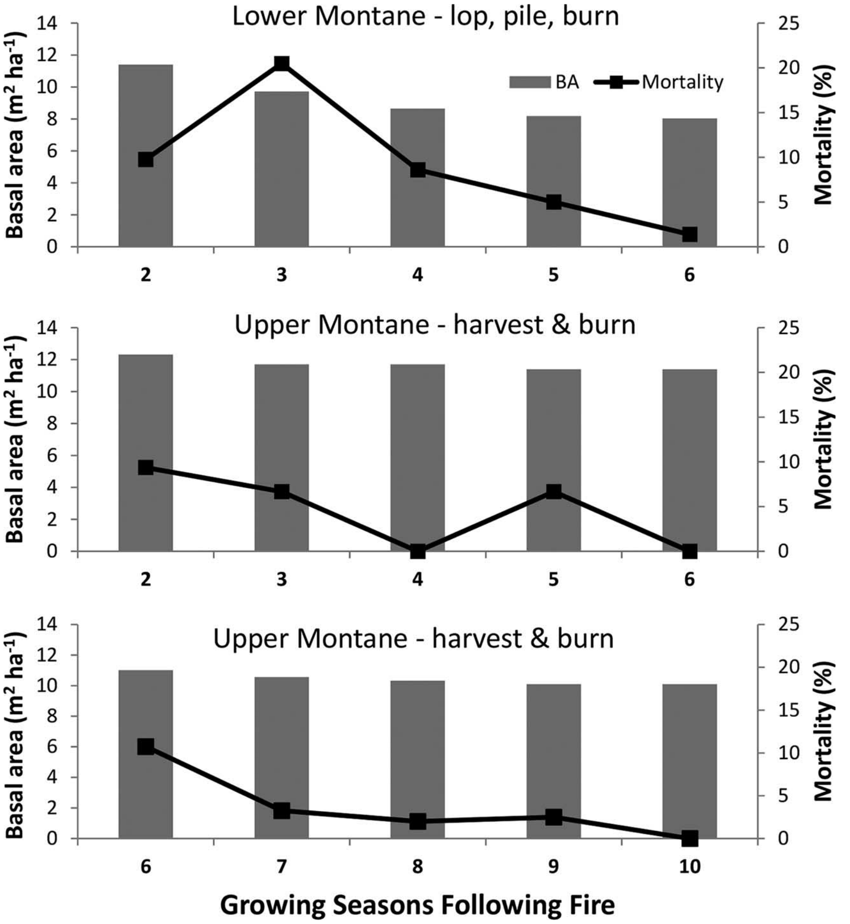

Figure 3. Five year (2003–2007) live basal area (m^2 ha^{-1}) and year-to-year overstory mortality (%) response on treated study sites in Arizona and New Mexico, USA, reported by GSF. Lower montane treatment included noncommercial LPB. Upper montane treatment included H&B 2–6 and 6–10 GSF. Tree mortality on lower montane L&S study sites was 100% immediately following fire and therefore not included in this figure.

scorched compared with the more severe 100% consumption as seen on untreated sites.

Discussion

Understory Cover and Standing Crop

Year Comparisons

A decrease in bare soil following fire on an annual basis is predictable, considering unique strategies (such as ruderal, competitive, and stress tolerant) (Grime 1977) adapted by plants for establishment in stressful and high disturbance environments (Lyon and Stickney 1976). Nonetheless, following high-severity fire on untreated sites on upper and lower montane sites, bare soil continued to characterize or dominate the understory cover 2–6 GSF despite the above-mentioned strategies (Figure 1). However, 8–10 GSF this characterization started to change on upper montane sites with increases in grass, forb, woody, and litter cover. Foxx (1996) reported that bare soil on two ponderosa pine study sites 16 years after high fire severity was 21 and 37%.

Numerous studies have reported increased herbaceous cover in the first 3 years following high-severity wildfire (Kuenzi et al. 2008). Foxx (1996) reported mean grass cover on high fire severity sites generally increased 1, 2, and 8 GSF and peaked at ~20% 8 and 16 years following wildland fire. We found similar peaks in grass and forb cover 2–4 GSF on high-severity lower montane sites. However, because of postfire reseeding treatments on these sites, the results were potentially confounded. Griffis et al. (2001) reported that an increase in forb abundance following high fire severity, an occurrence commonly reported in the literature (Crawford et al. 2001), was due to exotic species. We did not differentiate between native and exotic forbs when we estimated cover.

Woody cover response immediately following fire was predictable based on its ability to resprout (Fulé and Covington 1998). Oak competition can be expected due to its morphological and physiological adaptations to drought such as deep roots, xeromorphic leaves and means for efficient water transport (Abrams 1990). Kunzler and Harper (1980) reported increased dominance of Gambel oak following intense wildfires.

Standing crop measurements (kg ha^{-1}) are frequently used to characterize ecological status or "recovery" following fire (Pearson et al. 1972, Campbell et al. 1977, Bataineh et al. 2006). For example, Campbell et al. (1977) reported that herbage standing crop 2 years following fire increased ~3-fold on severely burned sites compared with prefire conditions, whereas Bataineh et al. (2006) reported understory standing crop 30 years following a wildland fire in northern Arizona was reduced in a drought year compared with that 8 years following fire. We found that standing crop estimates were generally less descriptive than cover estimates in assessing the ecological response to wildfire.

Treatment Comparisons

Untreated sites that burned at high severity were characterized by greater and persistent bare-soil exposure than treated sites. Bare soil persistence on untreated sites compared with that on treated sites (e.g., up to 10 GSF as seen on upper montane sites) may be an indicator of where burnout of large woody material caused deep soil heating (Brown et al. 2003). Monsanto and Agee (2008) reported that experimentally burned logs produced lethal surface temperatures up to 10 cm away laterally and temperatures damaging to cambial tissue up to 10 cm below the soil surface. Bare soil as a result of moderate and high fire severity may be susceptible to erosion, particularly within the first 3 years following fire (Robichaud et al. 2000).

Treated sites characterized by reduced fire severity had greater litter cover than untreated sites. Live conifer overstory, a result of reduced fire severity on H&B treatment sites, produced needle cast, whereas adjacent untreated sites characterized by 100% crown consumption lacked a source for needle cast. On L&S treatments, overstory conifer needles were scorched as opposed to consumed as a result of reduced fire behavior (Cram et al. 2006) and provided temporary soil cover for 2 GSF.

Grass cover increased through time on treated stands (as seen on upper montane H&B sites up to 10 GSF) versus untreated sites. Griffis et al. (2001) reported similar results 5 years following fire in terms of grass abundance where native grass abundance was greater on thinned and prescribed burned sites than on high fire severity sites. This disparity in grass cover was attributed to the disproportionately acute nature of the disturbance during high-severity fire (such as a smoldering duff layer) compared with the more conservative disturbance levels as prescribed in silvicultural treatments.

Woody cover response following fire is of interest because of its resilient nature and ability to resprout (Kunzler and Harper 1980, Abella and Fulé 2008). Savage and Mast (2005) reported that ponderosa pine stands recovering from crown fire were in some cases being converted to nonforested grass or shrub communities. Although there was no difference in woody cover in the short term (2–6 GSF) between treated and untreated sites, on upper montane sites 6–10 GSF woody cover was greater on untreated sites, suggesting a greater shrub component following multiple growing seasons following fire. Habitat types characterized by high fire severity may be susceptible to potential oak-dominated shrublands (Barton 2002). However, prefire woody species composition and structure may influence future stand structure. For example, Foxx (1996) reported a contrast in shrub cover on 2 high fire severity sites 16 years following fire (3 versus 16%).

Grazing managers may be interested in the general lack of differences in standing crop between treated and untreated sites regardless of GSF or the presence/absence of livestock grazing. Grazing allotments on lower montane sites were suspended following fire until three threshold criteria were simultaneously met: “fair” range condition; 112 kg ha^{-1} grass understory standing crop; and acceptable fence condition (Randall Chavez, USDA Forest Service, pers. comm., July 16, 2003).

Fuel Loading

Year Comparisons

Following moderate and high fire severity in lower and upper montane forests, managers can expect coarse woody debris (CWD) (dead and down woody material >7.62 cm in diameter) to begin increasing 4–5 GSF depending on local conditions. This information may be useful to safety officers concerned about falling rampikes, fire managers interested in planning prescribed fires, and ecologists interested in the role of CWD. Upper montane high-severity sites provided an extended look at what can be expected in terms of CWD 6–10 GSF: elevated and sustained loading in the absence of disturbance. Passovoy and Fulé (2006) reported similar results with CWD increasing 8–9 GSF and then remaining relatively persistent through 27 years on ponderosa pine sites in Arizona. Relatively slow decomposition rates in the arid southwest and lack of fire may help explain these results.

Lower montane fine woody debris (i.e., 1-, 10-, and 100-hour fuels) on moderate- and high-severity fire sites contributed to the overall fuel loading although the contribution in terms of biomass was considerably less than that of CWD. Unlike lower montane sites, fine woody debris on upper montane sites was unchanged 2–6 and 6–10 GSF. Stevens-Rumann et al. (2012) reported that fine woody debris trends were highly variable among fires.

Treatment Comparisons

Falling rampikes resulted in greater CWD on lower montane L&S and untreated sites than on LPB sites 6 years following high-severity fire. It should be noted the high-severity fire in the L&S treatments was attributed to the residual “scattered” activity fuels. Falling rampikes also resulted in greater fine woody debris (e.g., 100-hour fuel) loading 6 years after fire on untreated and L&S sites than on LPB sites. However, this was the extent of the differences in fine and coarse fuel loading among treatments 2–6 GSF on lower montane sites. Differences between treatments on upper montane sites were predominantly limited to greater CWD 6–10 GSF on untreated sites than on H&B sites.

Extensive and contiguous high-severity fires areas across the West have led to concerns about heavy surface fuel loads and their potential for repeated high-severity reburning (Brown et al. 2003, Monsanto and Agee 2008). However, there are also ecological benefits from CWD (Graham et al. 1994, Brown et al. 2003, Manies et al. 2005). Graham et al. (1994) and Brown et al. (2003) published recommended optimal ranges for CWD in ponderosa pine stands that can be used as guidelines from which to compare and make management decisions. Graham et al. (1994) recommended a range of 11–23 Mg ha^{-1}, whereas Brown et al. (2003) recommended a more liberal range of 11.2–44.8 Mg ha^{-1}. Two years after fire none of the treatments on lower or upper montane sites were within the recommended ranges (Table 3). However, untreated and L&S sites on lower and upper montane sites crossed the optimum threshold 5 years after fire. Untreated sites on upper montane sites remained within the optimum range for 6–10 years following fire. LPB treatments on lower montane sites and H&B treatments of upper montane sites were both below the recommended optimum range 2–6 and 6–10 GSF.

Given the conservative CWD fuel loadings noted above, the concern for high-severity reburning on our sites would be considered low. Brown et al. (2003) suggested that high reburn severity 0–10 years after stand replacement fire is probably not due to lack of duff and large accumulations of decayed 1,000-hour fuels. However, reburn severity 10–30 and 30–60 years following stand replacement fire in the absence of mitigation management could be significant (Monsanto and Agee 2008). Results from studies across the southwest indicate that various responses are possible. Stevens-Rumann et al. (2012) reported that CWD on a high fire severity site 9–10 years after fire in Arizona was greater than Brown et al.’s

(2003) upper limit, whereas Passovoy and Fulé (2006) reported that CWD loadings rose to within optimal ranges 8–9 years after fire but never exceeded the maximum value as proposed by Brown et al. (2003). Recommended CWD levels can be expected to vary, depending on the specific site circumstances such as quantity of small diameter woody fuel, landscape level needs, and ecosystem restoration objectives.

Overstory

Year Comparisons

We did not see any differences in annual mortality rates on lower or upper montane sites 2–6 GSF. Agee (2003) reported that immediate mortality as a result of prescribed fire was concentrated in smaller size classes, but larger and older tree mortality peaked 3–7 years following fire. Continued monitoring is necessary because 60% mortality of ponderosa pine over a 20-year period following prescribed fire has been reported (Harrington and Sackett 1990, Sackett et al. 1994).

Treatment Comparisons

From a visual standpoint, the difference in overstory structure (live versus rampike) between treated and untreated stands was conspicuous. Forest managers are interested in residual conifer mortality following fire on silviculturally treated sites as a way to evaluate prescription objectives and resiliency. Keyser et al. (2006) reported that the most important factor affecting tree mortality following fire was crown injury. Cram et al. (2006) reported that silvicultural treatments, in particular thinning and burning, reduced crown injury. We found that conifer mortality on treated sites generally decreased each year following fire. This provides evidence for managers that treated stands that experienced low fire severity can be expected to retain overstory structure through at least 10 growing seasons after fire, barring further disturbances (e.g., drought, insect, disease, and high-fire severity).

Conclusions

Ecosystem recovery after disturbance depends on opportunity and chance (Franklin et al. 1997). Proactive management using the full range of silvicultural tools can reduce fire severity and create desired stand conditions, depending on management objectives. This study suggests that pre-wildfire management treatments interacted with fire severity to have lasting effects on vegetation, fuel load, and stand structure response. Specifically, (1) untreated sites had persistent bare-soil exposure and less litter cover up to 10 GSF, (2) falling rampikes on untreated sites contributed to greater CWD 6–10 years following high fire severity than for treated sites, (3) few differences in standing crop (kg ha^{-1}) and fine fuel loading (1-, 10-, 100-hour fuels) among treatments were observed, and (4) annual tree mortality rates generally decreased each year following fire up to 10 years.

Endnote

1. For more information, see www.nifc.gov/fireinfo/fireinfo_statistics.html.

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