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RESEARCH ARTICLE

SHORT- AND LONG-TERM EFFECTS ON FUELS, FOREST STRUCTURE, AND WILDFIRE POTENTIAL FROM PRESCRIBED FIRE AND RESOURCE BENEFIT FIRE IN SOUTHWESTERN FORESTS, USA

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ABSTRACT

Prescribed and resource benefit fires are used to manage fuels in fire-prone landscapes in the Southwest. These practices, however, typically occur under different conditions, potentially leading to differences in fire behavior and effects. The objectives of this study were to investigate the effects of recent prescribed fires, resource benefit fires, and repeated fires in ponderosa pine forests, as well as recent resource benefit fires in pinyon-juniper woodlands. The Gila National Forest was the study area because it has a rich history of using fire as a restoration tool. In each vegetation type, fuels and stand structure were sampled using random plots stratified by burn severity in resource benefit fires. In ponderosa pine, sampling and analysis also included prescribed fire and areas subject to repeated resource benefit fires. To assess potential fire behavior, we used the crown fire behavior prediction model Nexus using ninetieth percentile weather conditions. In ponderosa pine forests, surface fuels were similar between prescribed fires and low severity resource benefit fires. However, resource benefit fires significantly reduced basal area, resulting in lower loading of canopy fuels and crown fire potential. Additionally, effects of resource benefit fire on stand structure and fuels seem to be sustained in areas that burned in two or three resource benefit fires in the last century. In pinyon-juniper woodlands, resource benefit low severity fires had no effect on surface or canopy fuel loads. Moderate severity resource benefit fires, on the other hand, did significantly reduce surface and canopy fuel loads. Results from this study are pertinent to fire and fuels managers throughout the southwestern United States who utilize prescribed and resource benefit fire to reduce fuel loads and restore historical forest conditions.

Keywords: Canopy bulk density, crown fire, fuel loading, prescribed fire

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INTRODUCTION

Fire has long been an important process that shapes forested ecosystems in the southwestern United States. In ponderosa pine forests, fires historically burned frequently with low intensity, resulting in relatively open stands (Covington and Moore 1994, Swetnam and Baisan 1996). It has been well documented and widely accepted that management practices and land use changes throughout the nineteenth and twentieth centuries have reduced fire frequencies and have led to substantial changes in ecosystem structure and function (Covington and Moore 1994; Moore *et al*. 2004). Despite vast fire suppression resources, recent wildfires in the southwestern US have made it clear that fire is an inevitable part of these forested ecosystems. In the future, wildfires are likely to be larger and more severe as a result of both climate change patterns and a century of fire suppression (Westerling *et al.* 2006). Although climate change itself is difficult to manage at regional and local scales, it is plausible to manage fuel conditions, stand structure, and fire regimes. It is therefore imperative that management objectives focus on reducing fuel loading and restoring the natural fire regime, using pre-settlement conditions as a guide even if the fire regime may change in the future (Allen *et al*. 2002).

Mechanical treatments and prescribed fire have been successfully utilized at small scales to reduce fuel loads and the potential for crown fire in high risk areas. However, numerous factors such as access, topography, and the lack of a timber industry in the southwestern US have prevented these strategies from being applied over large areas (Hunter *et al*. 2007). Resource benefit fires, because they often burn for several weeks, tend to cover more area. While total acreage burned in prescribed fires in the US currently exceeds that burned in resource benefit fires on an annual basis, data from the National Interagency Fire Center shows that the average fire size for the period 1998 to 2008 for resource benefit fires (234 ha [578 acres]) was more than twice that of prescribed fires (87 ha [214 acres]) (NIFC 2011). Thus, allowing resource benefit fires to spread across landscapes is likely to be an important mechanism of forest change at landscape scales. However, there are still a number of unresolved issues. For instance, while some research suggests that fire alone can be effective in reducing surface fuels (Sackett 1980), it may not be effective in reducing canopy fuels and restoring forest conditions to pre-settlement patterns (Fulé *et al*. 2002). On the other hand, Holden *et al.* (2007) have suggested that repeated fires have restored forest conditions to near pre-settlement conditions. Between these two extremes there is a substantial knowledge gap in terms of how different fire management strategies and burn severities impact fuels and potential fire behavior in both ponderosa pine forests and pinyon-juniper woodlands in the southwestern US.

Differences in fire effects on fuels and forest structure could stem from the application of prescribed fire versus resource benefit fire. Prescribed fire here refers to fire intentionally ignited by land managers under controlled conditions. Resource benefit fire (also known as prescribed natural fire and wildland fire use) here refers to lightning-ignited fire that is allowed to spread on its own accord without active suppression. To minimize the risk of escape, prescribed fire is often applied under a limited set of fuel and weather conditions that produce low fire severity and is completed in a matter of hours or days. On the other hand, resource benefit fire can spread for weeks and thus is typically subject to changing conditions of fuels, weather, and topography, resulting in a high degree of variability in fire behavior and effects. These different fire effects may be desirable or not, depending on management objectives. For example, the potentially higher burn severity associated with resource benefit fire may be more effective in reducing tree density, and thus the potential for crown fire spread. However, some have expressed concern that higher burn severity could also reduce loading of large down wood and snags, features that are critical for wildlife habitat (Horton and Mann 1988, Randall-Parker and Miller 2002).

To evaluate fire as a restoration or fuel reduction tool, it is also important to look not just at a single fire but also to examine the impact of repeated fires. Since ponderosa pine forest evolved under a pattern of repeated surface fires (Swetnam and Baisan 1996), one would expect that reintroducing frequent fire would lead to forests that are less susceptible to crown fire. Long-term studies of repeated prescribed fires in northern Arizona support this notion (Sackett *et al*. 1996). However, similar evaluations of repeated resource benefit fires are lacking, perhaps because of the limited utilization of this practice in the past. Studies in the Gila National Forest (NF) of New Mexico, USA, suggest that areas subject to repeated resource benefit fires still have adequate snag abundance (Holden *et al*. 2006) and tree density and structure, which resemble historical conditions (Holden *et al*. 2007). The effect of repeated resource benefit fires on other factors such as surface and crown fuel loading and the subsequent potential for crown fire spread remains largely unknown. This information is critical, given recent changes in US fire policy that allow land managers greater flexibility in utilizing resource benefit fire, and could potentially lead to greater adoption of this practice (USDA and USDI 2009).

In general, the use of prescribed fire has been more limited in pinyon-juniper woodlands because the fuel structure is not as conducive to low intensity fire spread. Unlike ponderosa pine forests, most pinyon-juniper woodlands in the Southwest historically burned in infrequent, stand replacing fires (Romme *et al*. 2003). In the Gila NF, resource benefit fires have recently spread through pinyon-juniper woodlands, producing various burn severities, and thus providing an opportunity to examine the effect of these fires on one of the most extensive vegetation types in the Southwest.

The Gila NF has a long history of managing resource benefit fire, dating back to the early 1970s (Webb and Henderson 1985). Conversely, fire suppression has been the standard practice of most land management agencies in the Southwest for much of the past century. Unlike most of the southwestern US, there are extensive areas of ponderosa pine forests in the Gila NF that have burned between two and four times with resource benefit fires in the last century. We used the unique landscape in the Gila NF as a setting to address three research questions:

1. What are the effects of recent (<5 yr) prescribed fires and resource benefit fires on fuel loads, stand structure, and potential fire behavior in ponderosa pine forests?
2. What are the prolonged effects of repeated resource benefit fires on fuel loads, stand structure, and potential fire behavior in ponderosa pine forests?
3. What are the effects of recent (<5 yr) resource benefit fires on fuel loads, stand structure, and potential fire behavior in pinyon-juniper woodlands?

METHODS

Study Site

This study was conducted in the Gila National Forest (NF), located in west-central New Mexico, USA. Elevation ranged from 1791 m to 2675 m. Forest types included those dominated by ponderosa pine (*Pinus ponderosa* C. Lawson) and those dominated by a mixture of pinyon pine (*Pinus edulis* Engelm.) and various juniper (*Juniperus deppeana* Steud., *Juniperus scopulorum* Sarg., and *Juniperus monosperma* [Engelm.] Sarg.) and oak (*Quercus gambelii* Nutt. and *Quercus grisea* Liebm.)

species. The study area typically receives 300 mm to 380 mm of precipitation each year, about half falling as snow in the winter months and half as rain in the summer months.

Study Design

We randomly established 0.02 ha plots in recent (<5 yr old) prescribed and resource benefit fires (Table 1). All prescribed fires occurred in areas that had not been previously thinned. To sample the impacts of resource benefit fires, we stratified stands within each fire perimeter, according to burn severity (moderate and low) and cover type (ponderosa pine and pinyon-juniper). We then randomly selected stands to be sampled. Within each selected stand, we established one plot in the center of the area. Burn severity was based on the burn area reflection classification, which is a satellite derived map comparing pre- and post-fire conditions. These maps depict soil burn severity and were taken from the Burn Area Emergency Response (BAER) website (http://activefiremaps.fs.fed.us/baer/download.php). These maps depict four levels of burn severity, including: unburned-low, low, moderate, and high. Given the relatively low frequency of high burn severity (<3 %) associated with each fire, we aggregated the moderate and high severity pixels into a moderate burn severity class. Similarly, we also aggregated the unburned-low and low severity pixels into a single low severity class for the sampling stratification. The cover type stratification was based on existing vegetation types (Eyre 1980) mapped by the LANDFIRE program (LANDFIRE 1.1.0) using predictive landscape models based on extensive field reference data, satellite imagery, biophysical gradient layers, and classification and regression trees. We used a similar plot selection process to sample the effects of prescribed fires. These types of fires, however, produce almost exclusively low burn severity and are rare in pinyon-juniper woodlands in this area. Therefore, this portion of the study focused on randomly selected sample plots within low burn severity areas within ponderosa pine forests. To address the objective of examining the effects of repeated resource benefit fires, we randomly established plots in ponderosa pine forests that burned two

Table 1. Description of study sites in the Gila National Forest, New Mexico, USA.

Treatment	Fire names[a]	Size (ha)	Year	Season	Severity	Vegetation type
PF[b]	Eckelberger (12) Sheep Basin (12)	7284 2486	2006 2005	Fall	Low	Ponderosa pine
RBF-L[c]	Martinez (16) Johnson (16) Bear (11)	3958 4699 22382	2006 2005 2006	Summer	Low	Ponderosa pine and pinyon juniper
RBF-M[d]	Martinez (17) Johnson (14)	3958 4699	2006 2005	Summer	Moderate-high	Ponderosa pine and pinyon juniper
Two RBF[e]	Unknown Ten Cow (20)	2028 5473	1946 2003	Summer	Low	Ponderosa pine
Three RBF[f]	Unknown Middle Bear (10)	780 5009 22382	1946 2002 2006	Summer	Low	Ponderosa pine

[a] Numbers in parentheses represent number of plots in each fire.
[b] Prescribed fire.
[c] Resource benefit fire—low severity.
[d] Resource benefit fire—moderate severity.
[e] Two resource benefit fires in the last century.
[f] Three resource benefit fires in the last century.

and three times within the last century. Such areas were found using historical fire perimeter datasets from Rollins *et al*. 2001, the Gila NF, and the Southwest Region of the US Forest Service (http://www.fs.fed.us/r3/gis/datasets.shtml). Although several areas met these criteria, most were located within the Gila Wilderness several miles away from the nearest road. Therefore, in order to reduce travel time, we elected to sample two areas that met these criteria but were outside the wilderness area. Because the ponderosa pine area that had experienced three fires was relatively small, we were only able to sample 10 plots. The ponderosa pine area that experienced two fires was larger and we were able to sample 20 plots.

To examine the impacts of fire, we compared burned plots to randomly selected plots that had not burned within the last century. We established unburned plots adjacent to sampled burned areas to ensure similar conditions prior to fire. We established unburned pinyon-juniper plots adjacent to sampled resource benefit fires. We established unburned ponderosa pine plots adjacent to sampled prescribed and resource benefit fires as well as areas with repeated resource benefit fires. In the field, we verified that plots established in unburned areas were in fact long unburned by looking for evidence of past fire (i.e., charred logs).

Data Collection

Plots were 0.02 ha with a circular layout. Within this area, we tallied all live and dead trees greater than 1.22 m tall. For each live tree, we recorded the following measurements: diameter at breast height (dbh), tree height, canopy base height (CBH), species, and crown ratio. For juniper, pinyon, and oak species, we recorded diameter at root crown instead of dbh. Height and dbh were recorded for all fire-killed trees. We also recorded scorch height and char height for all live and fire-killed trees. We tallied tree seedlings (<1.22 m tall) by species in a 50 m^2 subplot in the center of the main plot.

Starting from the center of each plot, we established three 25 m fuels transects. We determined the direction of the first transect by using a blind spin of a compass. The direction of the other two transects were 120° from the first transect. Using the methodology established by Brown *et al*. (1981), we measured loading of 1 hr, 10 hr, 100 hr, and 1000 hr fuels along these transects. We also established two subplots (1 m^2) at fixed locations (15 m and 25 m) along each transect in which we recorded percent cover of the following: grasses, forbs, shrubs, exotic species, litter, wood, rock, and bare soil. We recorded litter and duff depths in one corner of each subplot. We used four readings from a spherical densiometer in four cardinal directions to estimate canopy closure. Other variables that we measured at each plot include percent slope and aspect, measured with a clinometer and compass. Burn severity maps developed by BAER tend to focus heavily on fire severity as related to soil effects (Safford *et al.* 2007). Therefore, we also assessed fire severity in each recently burned plot using the composite burn index (CBI), which is an index of fire effects based on a number of factors, including surface fuel consumption, vegetation recovery, and tree mortality (Key and Benson 2006). The CBI was not assessed in unburned areas or in areas subject to repeated fires as these areas were not stratified by fire severity.

Data Analysis

Several estimates of canopy fuels are needed to predict crown fire potential, including canopy fuel load (CFL), canopy bulk density (CBD), and CBH. Multiple methods are available for estimating such metrics and no one method has yet gained wide acceptance. Allometric equations, like those developed by Brown (1978), are commonly used to estimate these variables as they are available for a variety of species. Also, stand-level regression equations developed by Cruz *et al*. (2003) are easy to use and have been widely applied.

Both methods can result in dramatically different estimates of canopy fuels and, thus, crown fire behavior prediction. Allometric equations generally result in more accurate assessments of canopy fuel characteristics (Reinhardt *et al*. 2006). While stand-level equations developed by Cruz *et al*. (2003) seem to overpredict canopy fuel characteristics, they can lead to more realistic predictions in crown fire behavior models (Roccaforte *et al*. 2008). Thus, there is good reason to examine multiple methods of estimating canopy fuels for the purpose of evaluating potential fire behavior.

We estimated canopy fuel characteristics using two methods to determine how these might influence crown fire behavior prediction. We used the Fuels Management Analyst (FMAPlus®, Fire Program Solutions, Sandy, Oregon, USA) model to estimate CFL and CBD for tree species based on allometric equations for several species. This model estimates all the foliage and >6 mm diameter branchwood for all trees in a defined area to calculate CFL because these fuels are thought to be most important for crown fire spread. The model calculates CBD across the canopy depth profile in 1 m vertical layers. Effective CBD is then calculated as the maximum 3 m running mean of these vertical layers. For species sampled but not represented in FMAPlus, we used similar species. For example, we used allometric equations for Gambel oak (*Quercus gambelii* Nutt.) for other oak species and allometric equations for one-seed juniper (*Juniperus monosperma* [Engelm.] Sarg.) for all juniper species encountered in the study. For plots in the ponderosa pine forest type, we also calculated CFL and CBD using stand-level equations developed by Cruz *et al*. (2003). Under this method, CFL and CBD are calculated from regression equations using stand basal area and tree density. Similar equations have not been developed for pinyon-juniper woodlands.

Another variable that was needed to assess the potential for crown fire initiation was a single value for CBH across a stand. For all vegetation types, we calculated this value as the twentieth percentile height to live crown of all trees in the plot. This has been shown to produce realistic estimates of predicted crown fire initiation compared to other methods, such as using minimum or average CBH (Fulé *et al*. 2002).

We used three variables to assess the potential for crown fire initiation and spread: CBD based on allometric equations (CBD-allometric), CBD based on stand-level calculations developed by Cruz *et al*. (2003) (CBD-stand), and the twentieth percentile CBH (CBH-20). Using the crown fire behavior model Nexus (Systems for Environmental Management, Missoula, Montana, USA) we determined what type of fire (surface, passive crown fire, active crown fire, or independent crown fire) would be predicted under average estimations of canopy fuel characteristics for each fire management strategy. Typical fuels and forest management objectives are to prevent crown fire spread under very dry conditions, which are represented by the ninetieth percentile weather. For this exercise, we assumed ninetieth percentile conditions for fuel moisture content (FMC) and windspeed measured at the Luna weather station in the Gila NF: 1 hr FMC = 3 %, 10 hr FMC = 3 %, 100 hr FMC = 9 %, woody FMC = 81 %, open windspeed = 17 mph.

We used univariate analysis of variance (ANOVA) to assess all the measured variables using SPSS© (IBM, Armonk, New York, USA). We tested all variables for normality and for homogeneity of variance using the Levene's test of equality of error variances. When assumptions were not met, we performed a square root or log transformation of the data. Untransformed data are presented in the results. We used the Tukey post-hoc test to examine differences between treatments. We determined significant differences for all tests with $\alpha = 0.05$. Univariate ANOVA determined that there were no significant differences in variables among different burned areas within a fire management strategy (i.e., Martinez versus Johnson fires; see Table 1). Thus, we combined variables from all fires within a fire management strategy in the analysis.

RESULTS

Based on the results of this study, it appears that low burn severity resource benefit fires had slightly greater impact than prescribed fires. While both fire management strategies resulted in low burn severity ratings (CBI < 1.5), low severity resource benefit fire had higher CBI ratings than prescribed fire ($F_{2,\,57} = 63.76$, $P < 0.001$) (Table 2). The CBI for remotely sensed moderate severity fire was in fact classified as moderate (CBI = 1.5 to 2) and was higher than the CBI from both low severity resource benefit fire and prescribed fire.

Fire management strategy or burn severity did not appear to have significant effects on surface fuels. There was no significant difference in 1 hr fuel loads ($F_{5,116} = 0.695$, $P = 0.628$) or 1000 hr fuel loads ($F_{5,116} = 0.373$, $P = 0.867$) among treatments (data not shown). The 10 hr fuel loads ($F_{5,116} = 2.950$, $P = 0.015$) were slightly less in areas burned in resource benefit fires of low severity compared to unburned areas, and 100 hr fuel loads ($F_{5,116} = 2.912$, $P = 0.016$) were slightly less in areas burned in resource benefit fires of low severity compared to prescribed fire (Table 2). Fire

Table 2. Average and standard error (in parentheses) of measured variables in ponderosa pine forests in the Gila National Forest, New Mexico, USA. Unburned areas are unburned for the last century. Numbers next to fire management strategy categories represents number of plots in each category. Different letters represent significant differences between fire management strategy categories for each measured variable. See Table 1 for description of fire management strategy categories.

Variable	Unburned (21)	PF (24)	RBF-L (31)	RBF-M (16)	Two RBF (20)	Three RBF (10)
CBI[A]	--	0.54 (0.09)^{a}	0.87 (0.09)^{b}	2.03 (0.11)^{c}	--	--
10 hr fuel load (Mg ha^{-1})	1.69 (0.21)^{b}	1.41 (0.19)^{ab}	0.86 (0.17)^{a}	1.75 (0.24)^{ab}	1.25 (0.21)^{ab}	1.06 (0.30)^{ab}
100 hr fuel load (Mg ha^{-1})	2.79 (0.51)^{ab}	2.63 (0.48)^{b}	0.90 (0.42)^{a}	2.72 (0.59)^{ab}	1.79 (0.52)^{ab}	0.96 (0.74)^{ab}
Litter depth (cm)	1.86 (0.14)^{b}	1.45 (0.14)^{b}	1.13 (0.12)^{ab}	0.83 (0.17)^{a}	1.00 (0.15)^{ab}	1.10 (0.21)^{ab}
Duff depth (cm)	0.62 (0.10)^{b}	0.57 (0.10)^{b}	0.30 (0.09)^{ab}	0.07 (0.12)^{a}	0.13 (0.11)^{a}	0.13 (0.15)^{a}
Forb cover (%)	4.19 (0.94)^{ab}	5.24 (0.88)^{b}	4.22 (0.77)^{b}	9.96 (1.07)^{b}	5.53 (0.96)^{b}	1.72 (1.36)^{a}
Grass cover (%)	10.80 (1.87)^{ab}	7.80 (1.75)^{a}	10.68 (1.54)^{ab}	7.17 (2.14)^{a}	13.49 (1.91)^{b}	26.04 (2.70)^{ab}
Soil exposure (%)	3.97 (1.46)^{ab}	3.30 (1.37)^{a}	5.51 (1.20)^{ab}	10.26 (1.67)^{b}	7.49 (1.50)^{ab}	6.28 (2.12)^{b}
BA (m^{2} ha^{-1})	27.91 (2.48)^{bc}	30.53 (2.32)^{c}	21.40 (2.04)^{b}	5.70 (2.84)^{a}	29.08 (2.54)^{bc}	25.40 (3.60)^{bc}
Trees ha^{-1}	933.33 (65.71)^{e}	552.08 (61.47)^{de}	380.65 (54.09)^{cd}	84.38 (75.29)^{a}	337.50 (67.34)^{cd}	310.00 (95.23)^{bc}
Tree seedling ha^{-1}	602.38 (65.03)^{b}	131.25 (60.83)^{ab}	45.16 (53.52)^{a}	15.63 (74.50)^{a}	72.50 (66.63)^{a}	30.00 (94.23)^{a}
CBD-stand (kg m^{-3})[B]	0.28 (0.02)^{d}	0.21 (0.02)^{cd}	0.15 (0.01)^{b}	0.03 (0.02)^{a}	0.15 (0.02)^{bc}	0.14 (0.03)^{bc}
CBD-allometric (kg m^{-3})[C]	0.15 (0.02)^{b}	0.12 (0.01)^{b}	0.10 (0.01)^{b}	0.04 (0.02)^{a}	0.11 (0.02)^{b}	0.15 (0.02)^{b}
CBH-20 (m)[D]	1.16 (0.49)^{a}	3.66 (0.46)^{b}	3.32 (0.40)^{b}	4.36 (0.56)^{b}	2.70 (0.50)^{ab}	4.91 (0.71)^{b}
Fire type-stand[E]	Active	Active	Passive	Surface	Passive	Surface
Fire type-allometric	Passive	Passive	Passive	Surface	Passive	Surface

[A] Only in this case, $n = 20$ for RBF-L. CBI ranges from 0 to 3; 0 = no effect; 0.5 to 1 = low severity; 1.5 to 2 = moderate severity; 2.5 to 3 = high severity.

[B] Canopy bulk density calculated using a stand-level regression equation.

[C] Canopy bulk density calculated using allometric equations.

[D] Twentieth percentile canopy base height.

[E] Predicted fire behavior in Nexus using ninetieth percentile weather conditions. Active represents active crown fire, passive represents passive crown fire, and surface represents surface fire.

management strategy did seem to have an impact on litter depth ($F_{3,68}$ = 6.895, $P < 0.001$), but only in moderate severity resource benefit fires. Duff depth ($F_{5,116}$ = 4.793, $P < 0.001$) was significantly lower in areas that burned in recent moderate severity resource benefit fires and in areas that burned in two or three resource benefit fires than in unburned areas and areas that burned in prescribed fires.

Understory vegetation cover was affected by both fire management strategy and burn severity. Cover of forbs ($F_{5,116}$ = 5.844, $P < 0.001$) was significantly less in areas that burned in three resource benefit fires compared to most other fire management categories (Table 2). Percent cover of grass ($F_{5,68}$ = 7.799, $P < 0.001$) appeared lower in areas that burned in prescribed fire or in moderate severity resource benefit fire, but differences were only significant within areas that burned in two resource benefit fires. Soil exposure ($F_{5,116}$ = 2.685, $P = 0.025$) was highest in moderate severity resource benefit fires, but differences were only significant within areas burned in prescribed fire.

Fire management strategy and burn severity did influence stand structure variables. For instance, basal area ($F_{5,116}$ = 11.508, $P < 0.001$) was significantly lower in moderate severity resource benefit fires than all other treatments (Table 2). Basal area was also significantly lower in low severity resource benefit fires than prescribed fires. However, there was no significant difference between areas that burned in two and three resource benefit fires and unburned areas. There was also a significant reduction in tree density ($F_{5,116}$ = 17.342, $P < 0.001$) in all resource benefit fires compared to the unburned areas. Conversely, tree density did not differ significantly between prescribed fires and unburned areas. Tree seedling density ($F_{5,116}$ = 11.697, $P < 0.001$) was lower in all resource benefit fire areas than in unburned areas. While tree seedling density was also lower in areas burned in prescribed fires than in unburned areas, differences were not significant.

Our results show that crown fuel conditions were also influenced by fire management strategy and burn severity. For example, CBD-stand ($F_{5,116}$ = 20.337, $P < 0.001$) was significantly lower in all resource benefit fire areas than in unburned areas (Table 2). Recent resource benefit fires of low and moderate severity also had significantly lower CBD-stand than prescribed fire. Differences in CBD-stand between prescribed fire and unburned areas were not significant. The CBD-stand was much lower in moderate severity resource benefit fires than in all other treatments. The CBD-allometric showed a similar trend ($F_{5,116}$ = 5.994, $P < 0.001$); however, it was only significantly lower in moderate severity resource benefit fires compared to unburned areas and all other treatments. The twentieth percentile canopy base height ($F_{5,116}$ = 5.979, $P < 0.001$) was significantly lower in unburned areas than in areas subject to prescribed and resource benefit fires. There was no significant difference in canopy base height in areas subject to different fire management strategies or in areas that were classified with different fire severity. Active crown fire was predicted in unburned areas and in areas subject to prescribed fires when using CBD-stand to model crown fire potential. Passive crown fire was predicted for areas subject to two resource benefit fires and recent low severity resource benefit fires. Surface fire was predicted for areas subject to three resource benefit fires and recent moderate severity resource benefit fires. A similar trend was seen when CBD-allometric was used, except that passive crown fire was predicted for unburned areas and areas subject to prescribed fires.

In pinyon-juniper woodlands, average CBI for areas remotely classified as moderate severity was significantly higher than areas classified as low severity ($F_{1,25}$ = 54.536, $P < 0.001$) (Table 3), and both ratings were consistent with BAER burn severity maps. Resource benefit fires had an impact on fuel loads only when they burned with moderate severity. The 1 hr fuel loads ($F_{2,46}$ = 4.870, $P = 0.012$) were

Table 3. Average and standard error (in parentheses) of measured variables in pinyon-juniper woodlands in the Gila National Forest, New Mexico, USA. Numbers next to each column header represent number of plots in each category. Different letters represent significant differences among categories for each measured variable. See Tables 1 and 2 for descriptions of abbreviations.

Variable	Unburned (22)	RBF-L (12)	RBF-M (15)
CBI	--	0.68 (0.15)^a	2.20 (0.14)^b
1 hr fuel load (Mg ha^{-1})	0.88 (0.15)^a	0.86 (0.20)^a	0.21 (0.18)^b
Litter depth (cm)	1.11 (0.10)^b	1.21 (0.14)^b	0.45 (0.12)^a
Duff depth (cm)	0.25 (0.06)^b	0.28 (0.07)^{ab}	0.04 (0.07)^a
Soil exposure (%)	5.42 (1.35)^a	9.01 (1.82)^a	16.17 (1.63)^b
Grass cover (%)	10.96 (7.24)^b	7.79 (6.53)^{ab}	5.70 (5.17)^a
Basal area (m^2 ha^{-1})	20.62 (6.26)^b	28.83 (18.78)^b	3.85 (10.24)^a
Trees ha^{-1}	681.82 (299.42)^b	641.67 (287.66)^b	93.33 (299.32)^a
Tree seedlings ha^{-1}	529.55 (713.75)^b	233.33 (333.26)^{ab}	30.00 (92.20)^a
CBD-allometric (kg m^{-3})	0.32 (0.14)^b	0.38 (0.26)^b	0.11 (0.29)^a
CBH-20 (m)	0.62 (0.53)^a	1.25 (0.49)^a	2.83 (1.66)^b
Fire type	Independent	Independent	Surface

significantly lower in moderate severity resource benefit fires compared to unburned areas. A similar trend was seen in the other fuel size classes, although the differences among fire severity classes were not significant (10 hr fuel: $F_{2,46} = 2.657$, $P = 0.081$; 100 hr fuel: $F_{2,46} = 2.009$, $P = 0.146$; 1000 hr fuel: $F_{2,46} = 0.518$, $P = 0.599$). Depths of litter ($F_{2,46} = 11.074$, $P < 0.001$) and duff ($F_{2,46} = 3.617$, $P = 0.035$) were significantly lower in moderate burn severity areas than in unburned areas, but there was no difference between areas classified as low burn severity and unburned areas. Soil exposure ($F_{2,46} = 12.992$, $P < 0.001$) was higher in moderate burn severity areas than in low burn severity and unburned areas. Percent cover of grass ($F_{2,46} = 3.027$, $P = 0.058$) was lower in moderate burn severity areas than in unburned areas. There was no significant difference in forb percent cover among burn severity classes ($F_{2,46} = 2.685$, $P = 0.079$).

Measures of pinyon-juniper stand structure and potential fire behavior were impacted only by moderate severity resource benefit fires. Basal area ($F_{2,46} = 16.948$, $P < 0.001$), tree density ($F_{2,46} = 19.855$, $P < 0.001$), and tree seedling density ($F_{2,46} = 4.404$, $P = 0.018$) were lower in moderate severity areas than in low severity or unburned areas (Table 3). Canopy bulk density ($F_{2,46} = 13.232$, $P < 0.001$) showed the same trend. Twentieth percentile canopy base height ($F_{2,46} = 21.348$, $P < 0.001$) was higher in moderate severity areas compared to low severity or unburned areas. Based on average stand structure, an independent crown fire was predicted in unburned areas and in areas classified as low severity, while a surface fire was predicted in areas classified as moderate severity.

DISCUSSION

In this study, we compared the ecological effects of two different fire management strategies, prescribed and resource benefit fire, on fuels, stand structure, and crown fire potential. In addition, we examined the long term effects and effectiveness of repeated resource benefit fires. In the strict sense, our study is pseudoreplicated (van Mantgem *et al.* 2001). Thus, extrapolation of results to other areas must be done with extreme caution. However, the fact that we examined multiple recent fires and multiple reference areas gives our results and interpretation greater credence. Our examination of prescribed and resource benefit fires was restricted to areas outside wilderness; however, we feel that the study still has merit: other studies in the Gila NF have focused exclusively in the wilderness area (Holden *et al*. 2006, 2007), and our results are applicable to managers who are beginning to apply resource benefit and prescribed fire outside of wilderness areas in the Southwest. With recent changes in fire policy (USDA and USDI 2009), more managers throughout the Southwest are either considering or have already begun implementing resource benefit fires. Thus, findings from this and other studies in the Gila NF provide key information for managers in similar forest types throughout the Southwest.

The inconsistencies in estimates of canopy bulk density produced by allometric and stand-level equations have been reported elsewhere (Reinhardt *et al*. 2006, Roccaforte *et al*. 2008); it is not surprising that we would find similar results. While no studies on the subject have been conducted in central New Mexico, in a similar forest type in northern Arizona, Reinhardt *et al*. (2006) found that allometric equations produced more accurate estimates of CFL and CBD than stand-level equations. It is unclear, however, how applicable these findings are for central New Mexico. While these respective regions have many similarities, ponderosa pine forests in the Gila NF do have a more prominent oak component that may influence the accuracy of allometric estimates of canopy fuels. Also, CBD based on allometric equations does not necessarily produce accurate estimates of potential fire behavior when used in fire behavior models (Roccaforte *et al*. 2008). This is perhaps because fire behavior models that are currently available tend to consistently underpredict crown fire potential (Cruz and Alexander 2010). Until there is development of better estimates of canopy fuels and better crown fire behavior models, multiple methods of estimating canopy fuels will need to be considered when evaluating crown fire potential.

The differences in fire effects on fuels between low burn severity resource benefit fires and prescribed fires are subtle but may be significant from the perspective of potential fire behavior. On the one hand, surface fuel loading and vegetation cover, which can recover more quickly after fire, were not dramatically different in prescribed and resource benefit fires. While both of these fire management strategies resulted in CBI classifications of low fire severity, low severity resource benefit fires resulted in slightly higher average CBI values than prescribed fires. As a consequence, basal area and CBD-stand were significantly lower in low severity resource benefit fires compared to prescribed fires. This difference in canopy fuels was enough to result in a difference in type of fire predicted by the fire behavior model Nexus. Similar differences in severity between prescribed fires and resource benefit fires have been documented in other forest types (van Wagtendonk and Lutz 2007). These results suggest that, while prescribed fires and resource benefit fires may have similar effects on surface fuels, resource benefit fires may be slightly more effective at reducing tree density and subsequent crown fire potential.

The contrasting fire effects observed in areas classified as low and moderate severity within resource benefit fires emphasize the importance of not over-generalizing fire as a homogeneous process. For instance, the fire effects observed within prescribed fires and low severity resource benefit fires are consistent with other studies (Fulé *et al*. 2002, Fulé *et al.* 2006, Collins *et al.* 2011), which have suggested that fire alone cannot restore pre-settlement conditions in ponderosa pine forests. However, this study also suggests that a single fire that burns with moderate severity can significantly reduce tree densities and basal area in ponderosa pine forests. The larger effects of moderate severity fires are also apparent in the canopy fuel profile in which we found dramatic reductions in canopy bulk density. Although historical conditions in southwestern ponderosa pine forest were highly variable, they typically ranged between 25 and 325 trees ha^{-1} (Moore *et al*. 2004, Fulé *et al*. 2002). Hence, these results show that a single fire of moderate severity alone can result in stand densities that more closely resemble pre-settlement conditions. In the areas that burned with moderate severity, current surface fuel loads fall within recommended levels for coarse fuels based on wildlife habitat needs and potential fire intensity (Brown *et al.*2003). However, surface fuel loads may increase over time as standing dead trees fall to the ground if fire is not returned to the system (Passovoy and Fulé 2006).

One potential undesirable effect of moderate burn severity is the increased risk of high severity burn patches within the moderate severity burn matrix. The fires we studied consisted of only a few moderate-high burn severity patches that were relatively small (<120 ha). This would indicate that these fires burned under moderate weather conditions and were mostly beneficial. Small pockets of high burn severity can be very effective at breaking up fuel continuity and creating wildlife habitat on a landscape (Rollins *et al*. 2001). On the other hand, larger patches of high burn severity can result in undesirable effects such as increased runoff and erosion, which may be detrimental to endangered species such as the Gila trout (*Oncorhynchus gilae*) (Brown *et al*. 2001). Moreover, high burn severity patches could result in complete tree mortality, loss of soil, and a possible complete type conversion (Strom and Fulé 2007).

Historical ponderosa pine forest structure was a product of not one but of a series of fires over time. Our findings show that repeated resource benefit fires can help maintain desired surface and canopy fuels levels through time. Like single fires, repeated fires did not have dramatic effects on surface fuel loading, with the exception of litter and duff depth. Repeated fires did, however, have substantial effects on stand structure such as tree density, tree seedling establishment, and canopy bulk density. Similar effects were seen in a study focused on the wilderness area within the Gila NF (Holden *et al*. 2007). A novel finding of this study was that ponderosa pine forests that have experienced repeated fire are predicted to experience passive crown fire or surface fire rather than active crown fire even under very dry weather conditions. This would suggest that these forests are better adapted to predicted climate change patterns that include more drought and severe fire weather conditions.

In pinyon-juniper woodlands, low burn severity resource benefit fires had almost no discernible effect on fuels or stand structure. For most surface and canopy fuel characteristics, areas that experienced low burn severity within resource benefit fires did not differ substantially from unburned areas. In most low burn severity areas, the fire appeared to burn very small areas, perhaps because the fuels in pinyon-juniper woodlands are generally not conducive to surface fire spread. Throughout the twentieth century, pinyon-juniper woodlands in the Gila NF burned very infrequently relative to the distribution of this vegetation type (Rollins *et al*. 2002), indicating that this vegetation type is fairly resistant to fire spread. Ecological effects were more dramatic in moderate burn severity areas, but these effects are probably not inconsistent with how these pinyon-juniper woodlands would have burned historically.

Overall, the results from this study suggest that there is a continuum of fire effects. These range from subtle effects associated with prescribed fires to substantial impacts associated with moderate severity resource benefit fires. In pinyon-juniper woodlands, low intensity prescribed fire may not be a viable option as this type of fire does not spread easily through this fuel type and tends to have very minimal effects on surface and canopy fuels. While resource benefit fires with moderate to high severity will produce dramatic effects in this vegetation type, it is probably consistent with how this system would have burned historically. Based on these results, it appears that, in ponderosa pine forest, fire alone is a viable tool for reducing crown fire potential. Moreover, this reduction can be achieved through the use of a single moderate severity fire and by restoring the natural fire regime of repeated low severity surface fires. The effects of low and moderate burn severity observed in this study are based on resource benefit fires. These effects, however, should be similar to those associated with unintended wildfires that result in low to moderate severity. Thus, this study provides important information to managers who utilize not only prescribed fire and resource benefit fire, but also apply minimal suppression on some wildfires, a strategy that is now acceptable under new policy guidelines (USDA and USDI 2009) and is likely to become more important as burn area increases with climate change.

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