Monitoring Effectiveness of Prescribed Fire and Wildland Fire Use in the Gila National Forest, New Mexico

Molly E. Hunter (PI)
School of Forestry
Northern Arizona University

Leigh B. Lentile (Co-PI)
University of the South

Jose M. Iniguez (Co-PI)
USDA Forest Service
Rocky Mountain Research Station

JFSP project 08-1-1-10

Joint Fire Science Program

Rocky Mountain Research Station

NORTHERN ARIZONA UNIVERSITY
School of Forestry

Abstract

Both prescribed fire and wildland fire use (resource benefit fire) can be used to manage fuels in fire-prone landscapes in the Southwest. These different practices typically occur at different times of the year and under different conditions, potentially leading to differences in fire behavior and effects. In this study we examine the effects of recent prescribed fires and wildland fire use fires on surface and canopy fuels in forested systems in central New Mexico. We also examine the long-term effects of repeated wildland fire use fires on surface and canopy fuels.

Recent prescribed fires and wildland fire use fires produced similar effects in terms of surface fuel loading. Wildland fire use fires resulted in slightly higher fire severity, as shown by a slightly higher mortality of tree saplings. This resulted in a lower loading of canopy fuels and thus the potential for crown fire spread. While both practices result in lower fuel loading, wildland fire use seems a bit more effective at reducing canopy fuels in ponderosa pine forests.

Wildland fire use fires that burned with low intensity in pinyon-juniper forests had no measurable effect on surface or canopy fuel loading. Only those areas that burned with moderate to high intensity did we find significant reductions in surface and canopy fuel loading. Given that low intensity surface fire does not spread readily through this system, prescribed fire is not likely to be a useful tool in these pinyon-juniper woodlands. Wildland fire use tends to burn with high intensity in this system, but this type of fire is probably not inconsistent with historical fires.

Areas that burned in two or three wildland fire use fires over the last 60 years had lower loading of surface and canopy fuels compared to areas that burned in one wildland fire use fire or are unburned in the last 60 years. Regardless of burning strategy (i.e. prescribed fire or WFU) these results indicated that repeated treatments are necessary to sustain desired conditions.

Background and purpose

Fire has long been an important process shaping forested ecosystems in the southwestern United States. In ponderosa pine systems in particular, fires historically burned frequently with low intensity, resulting in relatively open stand conditions (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 19th and 20th centuries have reduced fire frequencies and led to substantial changes in ecosystem structure and function, including higher tree density and increased potential for spread of high intensity crown fires (Covington and Moore 1994; Moore et al. 2004). Reintroduction of fire to these ecosystems, for the purpose of reducing fuel loading and the subsequent potential for crown fires, is now a common management objective. However, there are different methods in which one can reintroduce fire on a landscape. Fires can be ignited by land managers and allowed to burn under controlled conditions, a practice known as prescribed fire. In another, typically lesser used practice, fires naturally ignited by lighting are allowed to spread on their own accord. This practice has undergone several changes in policy which led to subsequent changes in what this practice has been labeled (i.e. prescribed natural fire, wildland fire use, and resource benefit fire) however the practice on the ground has remained fairly constant. For the purpose of this paper, we will use the term wildland fire use (WFU) since the fires we examined were implemented while this policy was in place and were labeled as such.

There are distinct differences in the practices associated with WFU and prescribed fire that may ultimately lead to very different effects. Perhaps the most important difference between prescribed and

WFU is that, as mentioned, prescribed fires are ignited by land managers whereas WFU are ignited naturally. Prescribed fires are typically applied under a limited set of fuel and weather conditions. To minimize the risk of escape, prescribed fire operations are often completed in a matter of hours or days, whereas WFU can spread for weeks. Over the course of several weeks, WFU events are often subject to changing conditions of fuels, weather, and topography. Thus, one can often expect a high degree of variability in fire behavior and effects with WFU compared to prescribed fire. Prescribed fire and WFU also typically occur at different times of year. Prescribed fires are typically initiated in the spring or fall, when weather conditions allow for more moderate fire behavior and thus better control. WFU often occurs in the summer, when lightning strikes are more frequent and fuels are relatively dry. This coincides with the season that fires likely occurred historically in the Southwest (Swetnam and Baisan 1996).

Differences in seasonality and fire behavior associated with prescribed fire and WFU could lead to substantial differences in fire effects, which may be desirable or not depending on objectives. For example, the higher intensity associated with WFU may be more effective in reducing tree density and thus the potential for crown fire spread. Prescribed fires can reduce surface fuel loading (Sackett 1980). Prescribed fire can also be effective in reducing tree density, depending on a variety of factors including fire intensity and season of burning (Harrington 1987; Sackett et al. 1996). However, some have expressed concern that high intensity fires may reduce loading of heavier, 1000-hr fuels and snags, landscape features that are critical for wildlife habitat (Horton and Mann 1988; Randall-Parker and Miller 2002). Recent changes in fire policy allow land managers greater flexibility for managing naturally ignited fires and could potentially lead to greater use of WFU (USDA and DOI, 2009). Since thorough examinations of WFU events are lacking, it is unclear if WFU is more, less, or equally as effective as prescribed fire in meeting resource management objectives while minimizing undesirable effects. Such information is needed as WFU becomes more widely used.

To successfully introduce fire to ecosystems, managers need to understand not only the immediate effects that result from fire, but also the prolonged effects that result from repeated fires. It has been suggested that mimicking the historical fire frequency as much as possible will result in the most desirable effects (Allen et al. 2002). Long-term studies of repeated prescribed fires in northern Arizona support this notion (Sackett et al. 1996). However, similar evaluations of WFU are lacking, perhaps because of the limited utilization of this practice. Studies in the Gila National Forest of New Mexico suggest that that repeated WFU events do not detrimentally impact snag abundance (Holden et al. 2006) and may be effective in reducing stand density (Holden et al. 2007). The effect of repeated WFU events on other factors such as surface and crown fuel loading and the subsequent potential for crown fire spread remains largely unknown.

Fire effects and behavior have been studied a great deal in ponderosa pine forests in the Southwest, however, much less is known about fire effects in pinyon-juniper woodlands. 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, although this depends on the type of pinyon-juniper woodland (Romme et al. 2003). In recent years we have seen high intensity wildfire spread through some pinyon-juniper woodlands, most notably in southwestern Colorado. In the Gila National Forest, WFU has recently spread through pinyon-juniper woodlands and burned with both low and high intensity. This provides an opportunity to gather information on the effects of fire in such systems which is greatly needed given the potential for them to be impacted as naturally ignited fires spread through these systems.

The Gila National Forest (GNF) in west-central New Mexico provides a unique landscape to address some of the unknowns surrounding WFU and prescribed fire. The GNF has a long history of WFU dating back to the early 1970s (Webb and Henderson 1985). With this 30+ year record of WFU, several areas have burned in multiple events and WFU has spread through multiple vegetation types. In addition, the GNF maintains an active prescribed fire program. We used the GNF as a setting to address the following research questions:

1) What are the effects of recent (less than 10 years old) WFU fires and prescribed fires on surface and canopy fuels in ponderosa pine forests?

2) What are the prolonged effects of repeated WFU fires on surface and canopy fuels in ponderosa pine forests?

3) What effects do recent (less than 10 years old) WFU fires have on surface and canopy fuels in pinyon-juniper woodlands?

Study description and location

<u>*Study design*</u>

Recent WFU and prescribed fires in ponderosa pine forests: To address the objective of comparing the effects of recent WFU and prescribed fire, plots were established in recent (<10 years old) WFU and prescribed fires. All prescribed fires occurred in areas that had not been previously thinned. Two prescribed fire and two WFU use events were examined (table 1; figure 1). WFU events tend to burn with much more varied severity patterns than prescribed fire. Within WFU fires plot locations were stratified according to high and low burn severity. The high burn severity class included both high and moderate severity classes and low burn severity class included both low and unburned areas within the fire perimeter. Plots were also established in nearby long-unburned areas (>60 years) to serve as controls. Since prescribed fire is rare in pinyon-juniper woodlands in this area, this portion of the study focused on ponderosa pine forests.

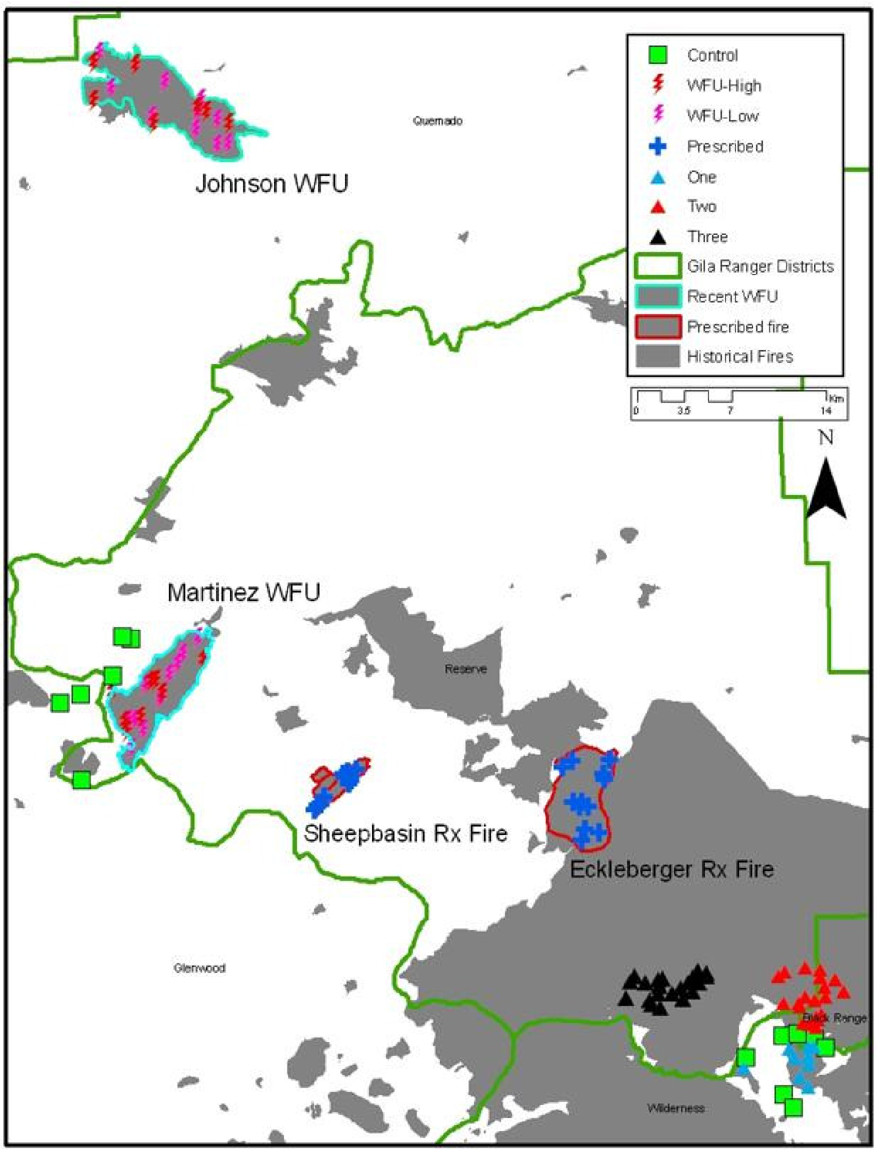
Table 1: Description of fires examined in the study

Fire name	***Fire type***	***Size (acres)***	***Vegetation types***	***Year***	***Season***
Eckleberger	Prescribed fire	18,000	Ponderosa pine	2006	Fall
Sheep Basin	Prescribed fire	6,143	Ponderosa pine	2005	Fall
Martinez	WFU	9,780	Ponderosa pine, pinyon-juniper	2006	Summer
Johnson	WFU	11,611	Ponderosa pine, pinyon-juniper	2005	Summer
A	WFU		Ponderosa pine	1993	Summer
B	WFU		Ponderosa pine	1946, 2003	Summer
C	WFU		Ponderosa pine	1938, 2003	Summer
D	WFU		Ponderosa pine	1946, 2003, 2006	Summer

Multiple WFU events in ponderosa pine forests: To address the objective of examining the effects of repeated WFU events, plots were established in areas that burned in one, two, and three WFU events in the last 60 years. Data from these plots were also compared to plots in long-unburned areas. Older WFU events in the Gila NF have occurred almost exclusively in ponderosa pine and mixed conifer forest types. Thus, we restricted this part of the study to ponderosa pine forests. Four different areas were examined (table 1; figure 1). Recent WFU fires in pinyon-juniper forests

Recent WFU fires in pinyon-juniper woodlands: Since little is known about the impacts of WFU fires in pinyon-juniper systems, we also established plots in these systems that burned in recent (<5 years old) WFU events. We again stratified the recent WFU events by fire severity (low and high). Long-unburned areas outside these fire perimeters served as unburned control areas. Plots were established in two separate WFU fires (table 1; Figure 1).

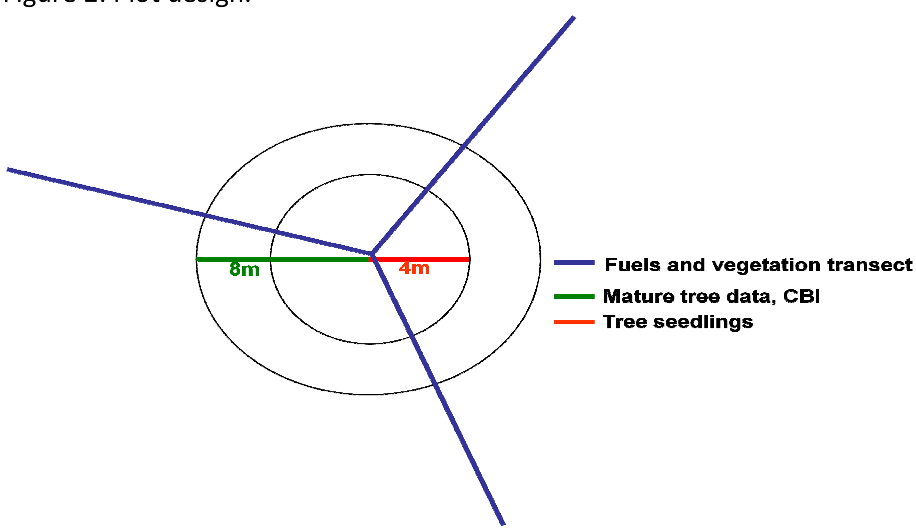
Figure 1: Map of study area in the Gila National Forest, NM.



Data collection
Plot layout was circular with a 16 m diameter (figure 2). Within this area all trees greater than 1.22 m tall were tallied. For each tree the following measurements were recorded: diameter at breast height (dbh), tree height, canopy base height (cbh), species, and crown ratio. For plots in recently burned areas, scorch height and char height were also recorded. Height and dbh was also recorded for all fire-killed trees. For juniper, pinyon, and oak species, diameter root crown was recorded instead of diameter at breast height. Tree seedlings (<1.22 m tall) were tallied by species in an 8 m diameter circular area in the center of the main plot.

Starting from the center of each plot, three fuels transects were established. Using the methodology established by Brown et al. (1981), loading of 1-hr, 10-hr, 100-hr, and 1000-hr fuels were assessed along these transects. Litter and duff depths were measured in two locations along each transect. Two subplots were also established along each transect in which percent cover of the following was recorded: grasses, forbs, shrubs, exotic species, litter, wood, rock and bare soil. Other variables that were measured at each plot include percent slope, aspect, and canopy cover. Fire severity was assessed in each recently burned plot using the composite burn index methodology developed by Key and Benson (2006).

Figure 2: Plot design.



Data analysis
Several estimates of canopy fuels are needed to run crown fire prediction models. These include canopy fuel load (CFL), canopy bulk density (CBD) and canopy base height (CBH). There is more than one method available to estimating such metrics and no one method has yet gained wide acceptance. Allometric equations developed by Brown (1978) are commonly used to estimate crown biomass as they are widely available for a variety of species. Stand-level equations developed by Cruz et al. (2003) have also been applied for their ease of use. Both of these methods can result in dramatically different estimates of canopy fuels and thus crown fire behavior prediction (Reihnardt et al. 2006; Roccaforte et al. 2008).

We estimated canopy fuel characteristics using two methods to determine how these might influence crown fire behavior prediction. Allometric equations from Brown (1978) were used to estimate canopy fuel load and canopy bulk density for ponderosa pine and Douglas-fir (*Pseudotsuga menziesii* (Mirb.)

Franco). The model Fuels Management Analyst (FMAPlus®) was used for this purpose (Carlton 2005). This model sums all the foliage and 0-6 mm diameter branchwood for all trees in a defined area to calculate canopy fuel load. It is these fuels are thought to contribute to crown fire spread. Canopy bulk density is calculated across the canopy depth profile in 1 m vertical layers. Effective canopy bulk density is then calculated as the maximum 3 m running mean of these vertical layers. Canopy fuel load and canopy bulk density were also calculated 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.

Different methods had to be utilized to calculate canopy fuel load and canopy bulk density for stands dominated by pinyon pine, juniper and oak species, since these species are not included in the original Brown (1978) and Cruz et al. (2003) equations. Instead, allomentric equations developed for pinyon pine and one seed juniper (*Juniperus monosperma* (Engelm.) Sarg.) (Grier et al. 1992) and Gambel oak (Clary and Tiedemann 1986) were used to calculate canopy fuel load for each plot. The allometric equations for Gambel oak were also used for other oak species found in the plots. Similarly, allometric equations for one-seed juniper were used for all juniper species encountered in the plots. Canopy bulk density was calculated by dividing computed canopy fuel load by canopy depth. Canopy depth was calculated as the difference between the 90th percentile tree height and median crown base height, a method that has produced reasonable results in previous studies (Reinhardt et al. 2006).

For all vegetation types, canopy base height was calculated as the 20th percentile height to live crown of all trees in a plot. This has been shown to produce reasonable estimates of predicted crown fire initiation compared to other methods such as using minimum or average canopy base height (Fulé et al. 2002).

Three variables were examined to assess the potential for crown fire initiation and spread; canopy bulk density based on crown fuel calculations developed by Brown (1978), canopy bulk density based on crown fuel calculations developed by Cruz et al. (2003), and the 20th percentile canopy base height. These fuel characteristics give some indication of the potential for passive and active crown fire. Throughout the report, the canopy bulk density variables are referred to as CBD-Brown and CBD-Cruz. Based on output from the fire behavior prediction model Nexus, we provide potential fire behavior for the observed range of fuel characteristics. For the exercise, we assumed 90th 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%, windspeed = 17 mph. This would be representative of very dry burning conditions.

All statistical tests were done using SPSS (Release 17.0.0, Aug. 23, 2008). Univariate analysis of variance (ANOVA) was used to assess all the measured variables. All variables were tested for homogeneity of variance before analysis using the Levene's test of equality of error variances. When assumptions for homogeneity were not met, the data were square root or log transformed. Untransformed data are presented in the results. The Tukey post-hoc test was used to examine differences between treatments. Significant differences for all tests were determined with $\alpha = 0.05$. Univariate ANOVA determined that there was no significant difference in variables among different burned areas within a fire type (i.e. Martinez vs. Johnson fires). Thus variables from all fires were combined in the analysis.

Results and Discussion

Recent WFU and prescribed fires in ponderosa pine forests: Recent prescribed fire and WFU fires resulted in slightly different fire effects. Average scorch height was significantly higher in high severity WFU areas compared to prescribed fire and low severity WFU areas and there was no significant difference between prescribed fire and low severity WFU (table 2). However, average dbh of fire-killed trees and percentage of fire-killed trees per plot indicate that low severity WFU had slightly more severe fire effects than prescribed fire as both of these variables were higher in low severity WFU compared to prescribed fire.

Table 2: Average scorch height (m), percentage of fire-killed trees, and average dbh of fire-killed trees in ponderosa pine areas (cm). Control areas are unburned for 60+ years. Prescribed fire areas are recently (2001-2008) treated with broadcast burns. WFU areas are recently (2004-2007) burned in wildland fire use. These areas were separated into areas that burned with high severity and low severity. Different letters represent significant differences between treatments for each fire severity characteristic. Numbers in parentheses represent *N* and *standard deviation* respectively.

Fire type	***Scorch height***	***% trees fire-killed***	***DBH fire-killed trees***
Control	0 (*12, 0*) a	0 (*12, 0*) a	N/A
Prescribed fire	1.201 (*24, 1.26*) b	5.375 (*24*, *12.77*) a	6.628 (*6,2.81*) a
WFU – high severity	7.166 (*16, 2.88*) c	86.563 (*16, 23.26*) b	17.439 (*16,4.01*) b
WFU – low severity	1.700 (*20,1.20*) b	22.925 (*20, 16.72*) c	11.673 (*16,5.71*) c

Fuel loading for only some size classes varied significantly by fire type (table 3). Both Ten-hour and 100-hr fuel loading was slightly lower in areas burned in low intensity WFU compared to other treatments, but was only significantly lower than the control. Litter depths were significantly lower in WFU events that burned with high and low severity, compared to the control (table 4). Percent cover of exposed soil was highest in the WFU-high severity treatment, and was significantly higher than the control and prescribed fire treatments (table 5).

Table 3: Average fuel loading (mg/ha) of plots in ponderosa pine areas. Numbers in parentheses represent *standard deviation.*

Fire type	***1-hr fuel load***	***10-hr fuel load***	***100-hr fuel load***	***1,000-hr fuel load***
Control	0.336 (*0.19*) a	2.125 (*1.11*) a	3.521 (*3.90*) a	23.306 (*30.24*) a
Prescribed fire	0.314 (*0.40*) a	1.406 (*0.88*) ab	2.633 (*2.18*) ab	18.383 (*22.57*) a
WFU – high severity	0.248 (*0.18*) a	1.748 (*1.27*) ab	2.718 (*2.91*) ab	21.863 (*21.71*) a
WFU – low severity	0.321(*0.25*) a	0.852 (*0.50*) b	0.913 (*0.96*) b	24.452 (*36.46*) a

Table 4: Average litter and duff depth (cm) in ponderosa pine areas.

Fire type	***Litter depth***	***Duff depth***
Control	1.983 (*1.32*) a	0.741 (*0.62*) a
Prescribed fire	1.453 (*0.52*) ac	0.566 (*0.44*) a
WFU – high severity	0.833 (*0.49*) b	0.068 (*0.15*) a
WFU – low severity	1.061 (*0.55*) bc	1.022 (*3.77*) a

Table 5: Average percent cover of forbs, grasses, and bare soil in ponderosa pine areas.

Fire type	***Forb cover***	***Grass cover***	***Bare soil cover***
Control	4.93 (*3.55*) ab	10.96 (*9.21*) a	4.07 (*3.64*) a
Prescribed fire	5.24 (*3.78*) a	7.80 (*3.90*) a	3.30 (*4.07*) a
WFU – high severity	9.96 (*8.53*) b	7.17 (*4.67*) a	10.26 (*8.23*) b
WFU – low severity	4.48 (*3.14*) a	7.38 (*6.83*) a	6.33 (*4.67*) ab

Basal area was significantly lower in both WFU treatments compared to prescribed fire and control treatments (table 6). Basal area was also significantly lower in high severity WFU areas compared to low severity WFU areas. Conversely, there was no significant difference between the prescribed fire and control treatments. There was also a significant reduction in tree density in both WFU treatments compared to the control. There was no significant difference between the prescribed fire and low severity WFU treatments, but both had higher trees per hectare than the WFU high severity treatment. While tree density appeared lower in prescribed fire treatments than in unburned areas, the differences between these treatments were not significant. Tree seedling density appeared lower in all treatments compared to unburned areas, but only the WFU treatments were significantly lower than the control.

Table 6: Average basal area (m^2/ha), number of trees per hectare, and number of seedlings per plot in ponderosa pine areas.

Fire type	***BA***	***TPH***	***Tree seedlings***
Control	31.92 (*9.15*) a	1054.17 (*595.61*) a	14.08 (*13.26*) a
Prescribed fire	30.53 (*12.79*) a	552.08 (*289.86*) ac	2.63 (*4.31*) ab
WFU – high severity	5.70 (*11.60*) b	84.38 (*149.13*) b	0.31 (*0.60*) b
WFU – low severity	20.23 (*9.94*) c	425.00 (*206.16*) c	1.00 (*2.37*) b

CBD-Cruz was significantly lower in both WFU treatments compared to the control and the prescribed fire treatment (table 7). CBD-Cruz for prescribed fire areas also appeared lower than the control, but differences were not significant. CBD-Cruz was much lower for WFU high severity plots compared to all other treatments. CBD-Brown was significantly lower in areas that burned with high severity WFU compared to all other areas. There was no significant difference among control, prescribed fire, and WFU-low intensity areas. The 20th percentile canopy base height for all treatments was significantly higher than the control. There was no significant difference in canopy base height among all the fire treatments.

Table 7: Average canopy bulk density (kg/m^3) and 20th percentile canopy base height (m). Two different values for canopy bulk density are given, one based on allometric equations developed Brown et al. (CBD - Brown), and one based on stand-level equations developed by Cruz et al. (CBD – Cruz).

Fire type	***CBD - Brown***	***CBD – Cruz***	***CBH-20***
Control	0.10 (*0.05*) a	0.32 (*0.11*) a	1.118 (*0.82*) a
Prescribed fire	0.15 (*0.18*) a	0.21 (*0.08*) a	3.658 (*2.84*) b
WFU – high severity	0.03 (*0.04*) b	0.03 (*0.06*) b	4.363 (*2.53*) b
WFU – low severity	0.09 (*0.05*) a	0.15 (*0.06*) c	2.530 (*1.29*) b

Multiple WFU events in ponderosa pine forests: Average fuel loading for 1-hr and 1,000-hr fuel loading did not differ significantly among treatments (table. 8). Loading of 10-hr fuels appeared lower in all treatments compared to the control, but only the two WFU treatment was significantly lower than the control. A similar trend was seen for 100-hr fuel loading.

Table 8: Average fuel loading (mg/ha) of plots in ponderosa pine areas. Number of fires represents the number of WFU events an area is subject to over a 60 year time frame. Areas with no recorded WFU have not experienced fire for 60+ years. Numbers in parentheses represent *N* and *standard deviation* respectively.

Fire number	***1-hr fuel load***	***10-hr fuel load***	***100-hr fuel load***	***1,000-hr fuel load***
None	0.336 (*12, 0.19*) a	2.125 (*12, 1.11*) a	3.521 (*12,3.90*) a	23.306 (*12, 30.24*) a
One	0.274 (*9, 0.31*) a	1.110 (*9, 0.69*) ab	1.807 (*9, 3.15*) ab	22.657 (*9, 27.66*) a
Two	0.140 (*20, 0.16*) a	0.972 (*20,0.69*) b	0.911 (*20,0.98*) b	10.247 (*20, 20.14*) a
Three	0.311 (*21, 0.22*) a	1.249 (*21, 1.14*) ab	1.791 (*21, 2.33*) ab	22.338 (*21, 34.01*) a

Litter depth was significantly lower in areas that burned two and three WFU events compared unburned areas (table 9). Litter depths in areas that burned in one WFU event were not significantly different than unburned areas. A similar trend was seen for duff depths. Forb cover was higher in areas that burned in three WFU events compared to areas that burned in two WFU events (table 10). Otherwise, there was no significant difference in forb cover among treatments. A similar trend was seen for grass cover, but differences between treatments were not significant.

Table 9: Average litter and duff depth (cm) in ponderosa pine areas.

Fire number	***Litter depth***	***Duff depth***
None	1.983 (*1.32*) a	0.741 (*0.62*) a
One	1.688 (*0.95*) ab	0.457 (*0.37*) ab
Two	1.189 (*0.38*) b	0.155 (*0.17*) b
Three	1.000 (*0.48*) b	0.126 (*0.16*) b

Table 10: Average percent cover of forbs, grasses, and bare soil in ponderosa pine areas.

Fire number	***Forb cover***	***Grass cover***	***Bare soil cover***
None	4.93 (*3.55*) ab	10.96 (*9.21*) a	4.07 (*3.64*) a
One	3.20 (*1.60*) ab	10.59 (*8.72*) a	3.83 (*4.23*) a
Two	2.79 (*1.97*) a	21.14 (*14.69*) a	5.10 (*3.33*) a
Three	5.53 (*3.90*) b	13.49 (*6.86*) a	7.49 (*12.27*) a

Number of trees per hectare was significantly lower in areas that burned in two or three WFU events compared to unburned areas (table 11). Tree density in areas that burned in only one WFU event was not significantly different from unburned areas. A similar trend was seen for number of tree seedlings. CBD-Cruz was significantly lower in areas that burned in two and three WFU events compared to control areas and areas that burned in one WFU event (table 12). The 20th percentile canopy base height was higher in areas that burned in two and three WFU events compared to areas that burned in no and one WFU events.

Table 11: Average basal area (m^2/ha), number of trees per hectare, and number of seedlings per plot in ponderosa pine areas.

Fire number	***BA***	***TPH***	***Tree seedlings***
None	31.92 (*9.15*) a	1054.17 (*595.61*) a	14.08 (*13.26*) a
One	22.58 (*11.32*) a	772.22 (*508.74*) ab	9.33 (*12.93*) ab
Two	24.42 (*9.31*) a	304.76 (*130.29*) b	0.67 (*1.35*) b
Three	29.08 (*12.89*) a	337.50 (*184.16*) b	1.45 (3.09) b

Table 12: Average canopy bulk density (kg/m^3) and 20th percentile canopy base height (m) needed to initiate torching in ponderosa pine areas.

Fire number	***CBD – Brown***	***CBD – Cruz***	***CBH-20***
None	0.10 (*0.05*) a	0.32 (*0.11*) a	1.118 (*0.82*) a
One	0.08 (*0.05*) a	0.23 (*0.14*) a	1.219 (*0.57*) a
Two	0.12 (*0.06*) a	0.14 (*0.04*) b	4.833 (*2.61*) b
Three	0.10 (*0.05*) a	0.16 (*0.07*) b	2.698 (*2.08*) c

Recent WFU events in pinyon-juniper forests: One-hour fuel loading was significantly lower in areas that burned with high fire severity compared to unburned areas (table 13). A similar trend was seen in the other fuel size classes, although the differences among treatments were not significant. Litter depths were significantly lower in areas that burned with high severity WFU compared to unburned and low severity WFU areas (table 14). Duff depth was also significantly lower in areas that burned in high severity WFU events compared to unburned areas. Duff depth also appeared lower in high severity WFU areas compared to low severity WFU areas, but differences were not significant. Cover of grasses was significantly higher in unburned areas compared to areas that burned in high severity WFU (table 15). Percent cover of exposed bare soil was higher in areas that burned with high severity WFU compared to low severity WFU and unburned areas.

Table 13: Average fuel loading (mg/ha) of plots in pinyon-juniper areas. Control areas are unburned for 60+ years. WFU areas are recently (2004-2007) burned in wildland fire use. These areas were separated into areas that burned with high severity and low severity. Numbers in parentheses represent *N* and *standard deviation* respectively.

Fire type	***1-hr fuel load***	***10-hr fuel load***	***100-hr fuel load***	***1,000-hr fuel load***
Control	0.881 (*22, 0.73*) a	1.607(*22, 1.92*) a	3.117 (*22, 3.03*) a	10.321 (*22,16.41*) a
WFU – high severity	0.213 (*15, 0.26*) b	0.463 (*15, 0.49*) a	1.684 (*15, 1.74*) a	6.640 (*15, 8.99*) a
WFU – low severity	0.862 (*12, 0.92*) a	1.281 (*12, 1.42*) a	1.800 (*12,1.67*) a	12.050 (*12,15.81*) a

Table 14: Average litter and duff depth (cm) in pinyon-juniper areas.

Fire type	***Litter depth***	***Duff depth***
Control	1.107 (*0.41*) a	0.245 (*0.26*) a
WFU – high severity	0.449 (*0.45*) b	0.042 (*0.07*) b
WFU – low severity	1.209 (*0.62*) a	0.275 (*0.38*) ab

Table 15: Average cover of forbs, grasses, and bare soil in pinyon-juniper areas.

Fire type	*Forb cover*	*Grass cover*	*Bare soil cover*
Control	6.08 (*3.65*) a	10.96 (*7.24*) a	5.42 (*4.37*) a
WFU – high severity	13.20 (*15.00*) a	5.70 (*5.17*) b	16.17 (*7.17*) b
WFU – low severity	7.17 (*7.97*) a	7.79 (*6.53*) ab	9.01 (*8.04*) a

Basal area was significantly lower in areas that burned with high severity WFU compared to unburned areas and areas that burned with low severity WFU (table 16). Tree density showed the same pattern. Tree seedling density was also lower in high severity WFU areas compared to unburned areas. Tree seedling density in low severity WFU areas was not significantly different from unburned areas or high severity WFU areas. The canopy bulk density was significantly lower in high severity WFU areas compared to unburned and low severity WFU areas (table 17). Canopy base height was higher in high severity WFU areas compared to unburned and low severity WFU areas. For each canopy fuel characteristic, there was no significant difference between unburned and low severity WFU areas.

Table 16: Average basal area (m^2/ha), number of trees per hectare, and number of seedlings per plot in pinyon-juniper areas. Different letters represent significant differences between treatments within each stand variable. Numbers in parentheses represent *standard deviation*.

Fire type	*BA*	*TPH*	*Tree seedlings*
Control	20.62 (*6.26*) a	681.82 (*299.42*) a	10.59 (*14.28*) a
WFU – high severity	3.85 (*10.24*) b	93.33 (*299.32*) b	0.60 (*1.84*) b
WFU – low severity	28.83 (*18.78*) a	641.67 (*278.66*) a	4.67 (*6.67*) ab

Table 17: Average canopy bulk density (kg/m^3) and 20th percentile canopy base height (m) in pinyon-juniper areas. Different letters represent significant differences between treatments within each stand variable. Numbers in parentheses represent *standard deviation*.

Fire type	*CBD*	*CBH – 20*
Control	0.016 (*0.01*) a	0.624 (*0.53*) a
WFU – high severity	0.005 (*0.01*) b	2.825 (*1.66*) b
WFU – low severity	0.023 (*0.01*) a	1.245 (*0.49*) a

Estimation of canopy biomass is something that foresters have been attempting to perfect for decades. As a result, allometric equations for tree canopy biomass are available for a variety of species. These allometric equations have been used to estimate canopy bulk density, a variable that is needed for crown fire prediction models. The specific methods used in this study have been shown to produce good estimates of canopy bulk density in ponderosa pine forests in the Southwest (Reinhardt et al. 2006). It is not clear however, if these methods result in the best estimates in terms of fire behavior. In another study, the Cruz estimates produced more reasonable estimates of crown fire potential when used in crown fire prediction models (Roccaforte et al. 2008). We found similar results in this study. Under 90th percentile weather conditions, only the Cruz estimates resulted in predictions of active crown fire using the model Nexus. Even in long-unburned stands with high tree density, no crown fire was predicted under 90th percentile weather conditions using the Brown estimates of canopy bulk density. Given the differences found between estimates here, it is clear that more work is needed not only on estimation of canopy fuels, but on how this relates to predicted crown fire behavior.

Not surprisingly, the effects produced by high severity WFU are dramatically different than low severity WFU and prescribed fire. The effects are especially apparent in the canopy fuel profile. Such effects may be desirable or not depending on the size of these high severity patches and management objectives. Pockets of high intensity fire can be very effective at breaking up fuel continuity and creating wildlife habitat on a landscape (Rollins et al. 2001). On the other hand, very large patches of high intensity fire 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). In the fires we studied most moderate-high severity patches were relatively small (< 120 hectares) and consisted of only a few small high severity patches. This would indicate these fires burned under moderate weather conditions and were mostly beneficial. Elsewhere however WFU fires have created large patches of complete mortality due to unanticipated weather event particularly high winds. This suggest that although moderate and high severity fires have the greatest impact in reducing tree densities such fire also have greater potential negatively impact resources including soils, water and aquatics resources. It appears that the differences in effects produced by low severity WFU and prescribed fire are subtle. Both of these events produced similar scorch heights.

The differences in effects produced by low severity WFU and prescribed fire are subtle but probably ecologically significant. Both of these events produced similar scorch heights, however low severity WFU results in slightly more tree mortality, as can be seen in the percentage of fire-killed trees in the plot and average dbh of fire-killed trees. Moreover only WFU resulted in tree mortality targets that are often part of fire management objectives for the Gila National Forest (20-30% of the stand). As a result, basal area and canopy bulk density (Cruz method) were slightly different between low severity WFU and prescribed fire. On the other hand, we found no dramatic differences in fuel loadings or vegetation cover between prescribed fire and WFU. These results suggest that while WFU and prescribed fire may be have similar effects on surface fuels, WFU may be slightly more effective at reducing tree density to more desirable levels.

One surprising result we found was that fuel loading did not differ significantly between unburned areas and areas that burned in WFU or prescribed fire. We can certainly assume that surface fuels would have been consumed during prescribed fire and WFU events. However, the time elapsed between the fires and the sampling may have been long enough to allow for fuel accumulation to reach pre-fire levels. Had we sampled these areas one year after the fires, we probably would have seen significant differences among treatments. The lack of significant differences among treatments could also be a function of the high degree of variability in fuel loading over a landscape.

It is clear from results that repeated WFU events produce prolonged effects that are not seen with single WFU events. Repeated events did not have dramatic effects on fuel loading, with the exception of litter and duff depths. Repeated events did have substantial impacts on stand characteristics such as tree density and tree seedling establishment. These changes in stand structure appear to be influencing the potential for crown fire spread as well, as areas that burned in multiple events showed lower canopy bulk density (Cruz method) and higher canopy base height compared to unburned areas and areas that burned in only one WFU event. Although high severity WFU significantly reduce tree densities, they also likely open the canopy and create ideal conditions for regenerations, therefore additional WFU will be needed to maintain these conditions. Similar effects were seen in a study focused on the wilderness area within the Gila National Forest (Holden et al. 2007). Since historical forest structure has not been explicitly examined in this area, we cannot determine if conditions resulting from these repeated WFU events result in conditions that reflect pre-Euro-American settlement. However, repeated WFU events are clearly reducing tree density, increasing height to live crown, and thus reducing the potential for crown fire spread.

In pinyon-juniper woodlands, low intensity WFU had almost no discernable effect on fuels or stand conditions. For most surface and canopy fuel characteristics, low intensity WFU did not differ much from unburned areas. In most areas classified as low severity, the fire appeared to burn a very small area, perhaps because the fuels in pinyon-juniper woodlands are generally not conducive to surface fire spread. Throughout the 20^{th} century, pinyon-juniper woodlands in the Gila NF burned very infrequently relative to the distribution of this vegetation type (Rollins et al. 2002). The areas that burned with high intensity of course had dramatic effects, but these effects probably not inconsistent with how these pinyon-juniper woodlands would have burned historically.

Ongoing work

In a related study, Jose Iniguez is examining tree age structure and spatial patterns in ponderosa pine and mixed conifer areas that have burned in multiple WFU events over the last 60 years. This study will provide important information on tree recruitment patterns following WFU events.

Future work needed

With this study we were able to highlight some differences between wildland fire use and prescribed fire. More information is needed to determine if these results apply in other parts of the country and with other WFU and prescribed fires. Such information can be gained by making monitoring of these effects a part of any fire event. In an attempt to encourage monitoring of effects, we provided the Gila NF fire personnel with simple monitoring protocols that we used in this study.

One thing that became evident in this study was the need for better understanding of estimating canopy fuel loads and how this relates to fire behavior models. When using two different, but commonly used techniques for estimating canopy fuel load and canopy bulk density, we got very different results. While one method (Brown) has been shown to produce more accurate estimates of canopy bulk density in other parts of the Southwest (Reinhardt et al. 2006), it resulted in unrealistic fire behavior prediction when used in conjunction with Nexus, a result that has been found elsewhere (Roccaforte et al. 2008).

Deliverable crosswalk

Deliverable	Description	Status
Presentation	Presentation on findings of study given to fire managers at annual Gila NF fire manager meeting. **Leigh B. Lentile**, Molly E. Hunter, Jose M. Iniguez. Effects of prescribed fire and fire use in the Gila National Forest.	Completed April 2010
Presentation	Presentation on future study plans give to fire managers at annual Gila NF fire manager meeting. **Jose M. Iniguez**, Molly E. Hunter, Leigh B. Lentile	Completed April 2010
Publication	Description of monitoring protocols used in the study. Molly E. Hunter, Leigh B. Lentile, and Jose M. Iniguez.	Given to Gila NF personnel

		May 2010
Presentation	Presentation on findings of the study given at the Association for Fire Ecology meeting in Savannah, GA **Molly E. Hunter,** Leigh B. Lentile, and Jose M. Iniguez. Effects of prescribed fire and fires use in the Gila National Forest, USA.	Completed Fall 2009
Presentation	Presentation on effects of prescribed fire and WFU in fire manager training courses. NAU courses where data from project have been used: *Fire Ecology, Fire Monitoring and Modeling, Fuel Treatments and Modeling*	Completed Fall 2009 and Spring 2010
Publication	Peer-reviewed publication in Forest Ecology and Management Molly E. Hunter, Leigh B. Lentile, and Jose M. Iniguez. Short- and long-term effects of different fire management practices in the Gila National Forest, New Mexico, USA.	Publication in review
Publication	Popular publication – working paper highlighting summary of findings Molly E. Hunter, Leigh B. Lentile, and Jose M. Iniguez. Monitoring results from prescribed fires and WFU fires in the Gila National Forest, NM	Given to Gila NF fire personnel May 2010

References

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman, and J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective. Ecological Applications 12: 1418-1433.

Brown, J.K. 1978. Weight and density of crowns of Rocky Mountain conifers. USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper INT-197.

Brown, J.K., Oberheu, R.D., and Johnston, C.M. 1981. Handbook for inventorying surface fuels and biomass in the Intermountain West. USDA Forest Service, Rocky Mountain Research Station Gen. Tech. Rep. INT-129. Ogden, UT.

Brown, D.K. Echelle, A.A., Propst, D.L., Brooks, J.E., and Fisher, W.L. 2001. Catastrophic wildfire and number of populations as factors influencing risk of extinction for Gila trout (*Oncorhynchus gilae*). Western North American Naturalist 61: 139-148.

Carlton, D. 2005. Users' guide to using the CrownMass and Fuel Model Manager programs. Fire Program Solutions LLC, Sandy, Oreg.

Clary, W.P. and Tiedemann, A.R. 1986. Distribution of biomass within small tree and shrub form *Quercus gambelii* stands. Forest Science 32(1): 234-242.

Covington, W.W. and M.M. Moore. 1994. Postsettlement changes in natural fire regimes and forest structure: Ecological restoration of old-growth ponderosa pine forests. Journal of Sustainable Forestry 2: 153-181.

Cruz, M.G., Alexander, M. E. and Wakimoto, R.H. 2003. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. International Journal of Wildland Fire 12(1): 39-50.

Grier, C.C., Elliot, K.J., and McCullough, D.G. 1992. Biomass distribution and productivity of *Pinus edulis-Juniperus monosperma* woodlands of north-central Arizona. Forest Ecology and Management 50: 331-350.

Fulé, P.Z., Covington, W.W., Smith, H.B., Springer, J.D., Heinlein, T.A., Huisinga, K.D., and Moore, M.M. 2002. Comparing ecological restoration alternatives: Grand Canyon, USA. Forest Ecology and Management 170: 19-41.

Harrington, M.G. 1987. Ponderosa pine mortality from spring, summer, and fall crown scorching. Western Journal of Applied Forestry 2: 14-16.

Holden, Z.A., P. Morgan, M.G. Rollins, and R.G. Wright. 2006. Ponderosa pine snag densities following multiple fires in the Gila Wilderness, New Mexico. Forest Ecology and Management 221: 140-146.

Holden, Z.A., Morgan, P., Rollins, M.G., and Kavannagh, K. 2007. Effects of multiple wildland fires on ponderosa pine stand structure in two southwestern wilderness areas, USA. Fire Ecology 3: 18-33.
Horton, S.P. and Mann, R.W. 1988. Effects of prescribed fire on snags and cavity-nesting birds in southeastern Arizona pine forests. Wildlife Society Bulletin 16: 37-44.

Key, C.H. and Benson, N.C. 2006, Landscape assessment (LA), Sampling and analysis methods, USDA Forest Service Gen. Tech. Rep, RMRS-GTR-164-CD. (Ogden, UT) 51 pp.

Moore, M.M., D.W. Huffman, P.Z. Fule, and W.W. Covington. 2004. Comparison of historical and contemporary forest structure and composition on permanent plots in southwestern ponderosa pine forests. Forest Science 50: 162-176.

Randall-Parker, T. and Miller, R. 2002. Effects of prescribed fire in ponderosa pine on key wildlife habitat components: Preliminary results and a method for monitoring. In: W.F. Laudenslayer et al. eds. Proceedings of the symposium on ecology and management of dead wood in western forests, Nov 2-4, 1999, Reno, NV. Gen. Tech. Rep. PSW-GTR-181. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Reinhardt, E., Scott, J., Gray, K., and Keane, R. 2006. Estimating canopy fuel characteristics in five conifer stands in the western United States using tree and stand measurements. Canadian Journal of Forest Research 36:2803-2814.

Roccaforte, J.P., Fulé, P.Z., and Covington, W.W. 2008. Landscape-scale changes in canopy fuels and potential fire behavior following ponderosa pine restoration treatments. International Journal of Wildland Fire 17:293-303.

Rollins, M.G., Swetnam, T.W., and Morgan, P. 2001. Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. Canadian Journal of Forest Research 31: 2107-2123.

Rollins, M.G., Morgan P., and Swetnam, T. 2002. Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landscape Ecology 17:539-557.

Romme, W.H., Floyd-Hanna, L. and Hanna, D.D. 2003. Ancient piñon-juniper forests of Mesa Verde and the West: A cautionary note for restoration programs. In: Omi, P.N. and Joyce, L.A., eds. Fire, fuel treatments and ecological restoration: Conference proceedings; 2002 16-18 April; Fort Collins, CO. Proceedings RMRS-P-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Sackett, S.S. 1980. Reducing natural ponderosa pine fuels using prescribed fire: Two case studies. Res. Note RM-RN-392. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Sackett, S.S., Haase, S.M., and Harrington, M.G. 1996. Lessons learned from fire use for restoring southwestern ponderosa pine ecosystems. In: W.W. Covington and M.R. Wagner, eds. Conference on adaptive ecosystem restoration and management: Restoration or Cordilleran conifer landscapes of North America. Gen. Tech. Rep. RM-GTR-278. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Scott, J.H. and Reinhardt, E.D. 2004. 'NEXUS 2.0.' Software program. Systems for Environmental Management: Missoula, MT.

Swetnam, T.W. and Baisan, C.H. 1996. Historical fire regime patterns in the southwestern United States since AD 1700. In: C.D. Allen, ed. Fire effects in southwestern forests: Proceedings of the La Mesa fire symposium. Gen. Tech. Rep. RM-GTR-286. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Swetnam, T.W. and Dieterich, J.H. 1985. Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. In: Lotan, J.E. et al. (eds.) Proceedings – symposium and workshop on wilderness fire. GTR-INT-182. USDA Forest Service Intermountain Research Station, Ogden, UT, USA, pp: 29-35.

SPSS for Windows, Rel. 17.0.0. 2008. Chicago, IL. SPSS Inc.

USDA and DOI. 2009. Guidance for implementation of federal wildland fire management policy.

Webb, D.R. and Henderson, R.L. 1985. Gila wilderness prescribed natural fire program. In: Lotan, J.E. et al. (eds.) Proceedings – symposium and workshop on wilderness fire. GTR-INT-182. USDA Forest Service, Intermountain Research Station, Ogden, UT, USA, pp 413-414.