Evaluation of silvicultural treatment effects on infiltration, runoff, sediment yield, and soil moisture in a mixed conifer New Mexico forest

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ABSTRACT: Clearing ponderosa pine forests often increases post-harvest runoff and sediment yield, yet there is little research to show if partial thinning of mixed conifer forests similarly produces more runoff and sediment. Rainfall simulations were used to evaluate silvicultural treatment effects on infiltration, runoff, sediment yield, and soil moisture in a southern New Mexico mixed conifer forest. Silvicultural treatments included: untreated control; precommercial thin with slash piled; and precommercial thin with slash scattered. There were no significant differences in infiltration rates, runoff rates, or soil moisture. Time to peak runoff was greater on pile and scatter treatments than on the control during both dry and wet runs. Sediment yield was greater on pile and scatter treatments than on the control during wet runs, yet was very low in all cases. We conclude that southwestern mixed conifer forests may be partially thinned without risk of significant increases in hillslope runoff and sediment yield.

Keywords: Precommercial thin, rainfall simulation, water quality, water yield, wildfire danger

Tree densities in southwestern U.S. forests have increased considerably over the last century. Prior to European settlement, many southwestern forests were described as open and park like, supporting diverse herbaceous plants (Cooper, 1960; Weaver, 1964). Today many of these forests have higher tree densities than historic densities. Tree densities have increased because of the lack of fire (Swetnam, 1990; Allen et al., 1995; Touchan et al., 1995). Historically, fires acted naturally to thin forests and maintain healthy open stands (Swetnam and Baisan, 1996). Frequent surface fires consumed herbaceous vegetation, litter, small trees, and ladder fuels (Swetnam and Baisan, 1996). In the past, fire return intervals for southwestern forests ranged from two to 12 years in ponderosa pine forests (Weaver, 1951; Cooper, 1960; Dieterich, 1980) and from 15 to 30 years in mixed conifer forests (Swetnam, 1990; Allen et al., 1995). Widespread fire has been absent from most southwestern forests for the past century beginning with a period of intensive livestock grazing, which occurred in the late 1800s and removed fine fuels required to carry surface fires over the landscape (Swetnam, 1990). The frequency and spread of natural fires in the southwest was further reduced by active fire suppression, which occurred throughout the 1900s (Swetnam, 1990; Swetnam and Betancourt, 1990; Allen et al., 1995; Touchan et al., 1995; Swetnam and Baisan, 1996) and continues today.

Natural resource management problems associated with increased forest density include: reduced water yield (Trimble and Weirich, 1987; MacDonald and Stednick, 2003), reduced herbaceous vegetation (Cooper, 1960; Oliver and Ryker, 1990), and increased wildfire danger (Swetnam, 1990). Today, wildfire danger is far too great to utilize prescribed burning as a primary restoration tool in many places. Hazardous fuels must be reduced before fire can be used (Cooper, 1960; Allen, 1994). To reduce forest density, many land managers are turning to combinations of silvicultural treatments followed by prescribed fire. Silvicultural treatments are able to reduce tree density and rearrange woody fuels so that fire can be utilized to further reduce forest fuels. Research has shown that reducing ponderosa pine forest tree density promises to increase water yield (Bosch and Hewlett, 1982; Stednick, 1996), increase forage production (Cooper, 1960; McConnell and Smith, 1965; Jameson, 1967), and reduce wildfire danger (Cram et al., 2003). Sediment yield associated with silvicultural treatments may be an important treatment limitation (USFS, 1981; Stednick, 2000; MacDonald and Stednick, 2003). The Clean Water Act of 1972 developed regulatory requirements to protect water quality (MacDonald and Stednick, 2003). For Clean Water Act compliance, it is important that silvicultural treatments minimize erosion when they are implemented in forests containing streams. Research is needed to document the effects of forest management activities in southwestern mixed conifer forests.

This research was designed to provide scientific knowledge to land and water managers to help them better manage water resources and forest soils and to help in selection of appropriate thinning prescriptions that will meet their goals. The purpose of this study in a mixed conifer forest in New Mexico was to determine, with simulated rainfall, forest silvicultural treatment effects on: 1) runoff, infiltration, and sediment yield; and 2) soil moisture content. Three silvicultural treatments were evaluated: 1) untreated control ("control"); 2) precommercial thin with slash piled ("pile"); and 3) precommercial thin with slash scattered ("scatter"). A precommercial thin is a treatment in which noncommercial timber is harvested manually to reduce fire danger and promote forest health (Mickey Mauter, USFS, personal communication, 2005). We hypothesized that disturbance on the pile and scatter treatments would result in reduced infiltration,

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increased runoff, and increased sediment yield. We also hypothesized that soil moisture content during simulated rainfall would differ among treatments with greater soil moisture on the control treatment than on pile and scatter treatments.

Materials and Methods

This study was conducted from 2003 to 2005 with fieldwork completed from August to October 2004 within the "Pumphouse" U.S. Forest Service (USFS) grazing allotment in the Lincoln National Forest near Cloudcroft, New Mexico (lat. 32° 56.46'N, long. 105° 44.03'W). Mean annual precipitation at the study site is 584 mm (23 in) (NRCS, 2003). During the summer months, high intensity (11.0 cm hr^{-1}; 4.32 in hr^{-1}) (NOAA, 2003), short duration thunderstorms are common in the Cloudcroft area (NRCS, 2003). Average annual temperature is 7.2°C (45°F) with extremes of -32.2°C (-26°F) in winter to 37.8°C (100°F) in summer (NRCS, 2003).

The topography is relatively steep with most slopes ranging from 20 to 40 percent. Elevation ranges from 2560-2774 m (8400-9100 ft). Soils on the study site are classified as Typic Argiustolls, Pachic Udic Argiustolls, and Lithic Argiustolls ranging in texture from a clay loam to a silt loam (Bob Dancker, USFS, personal communication, 2005). Vegetation type is mixed coniferous forest dominated by Douglas fir (Pseudotsuga menziesii), with a ponderosa pine (Pinus ponderosa) component.

The treatment areas were harvested manually by Forest Service crews using a "Low Intensity Thin," harvesting noncommercial timber less than 22.9 cm (9 in), diameter at breast height and maximum of 4.9 m (16 ft) spacing during the summer and fall months of 2003 (Glenn Mason, NMSU, personal communication, 2005). The precommercial thin was a light thinning treatment, with averages of 418 trees ha^{-1} (169 trees ac^{-1}), on the pile site and 458 trees ha^{-1} (185 trees ac^{-1}), on the scatter site compared to 610 trees ha^{-1} (247 trees ac^{-1}), on the control site following treatment. In pile treatments, small diameter timber was harvested and all slash was piled. In scatter treatments, small diameter timber was harvested and slash was lopped and scattered. Precommercial treatments are common throughout national forests in the western U.S., especially at the wildland-urban interface (Doug Porch and Jordan Wood, USFS, personal communication, 2005). Precommercial treatments are light thinnings compared to commercial treatments that open the canopy. The intent of precommercial treatments is to provide a short-term reduction in hazardous ladder fuels and promote forest health.

Since treatments were done by hand and no heavy equipment was used there was minimal ground disturbance and disturbance was relatively homogenous at the stand scale. Ground disturbance on the pile treatment ranged from no disturbance to slight roughing of the litter with slight exposure of mineral soil in areas where slash was hauled to piles. The pile treatment contained a few slash piles, but ground cover of small branches, twigs, and pine needles was representative of the treatment. Ground disturbance on the scatter treatment ranged from no disturbance to slight roughing of the litter.

Our study design took advantage of a concurrent study, conducted by the Range Improvement Task Force of New Mexico State University, to determine effects of silvicultural treatments on fuel loading and plant response. In the concurrent study, three contiguous forest stands per silvicultural treatment were selected post-harvest, with two randomly located 100-m (328-ft) permanent transects within each stand. For our study, ten plots were randomly located along the existing transects in each silvicultural treatment. In order to randomly locate plots, a tape measure was stretched out along permanent transects. A random number was selected and located on the tape. A random direction was taken from the second hand of a watch and ten meters were measured in the random direction. The plot ring was installed at this point. The randomization procedure did not yield any plot locations on slash piles or trees, probably because of the small number of piles and spacing of remaining trees.

Rainfall simulations were used to provide controlled conditions for evaluating infiltration, runoff, sediment yield, and soil moisture on the plots, which had steep slopes ranging from 17 to 27 percent. Rainfall simulations were conducted with a portable rainfall simulator (Wilcox et al., 1986), with a 1/4G10 full jet nozzle (Spraying Systems Co., Wheaton, Illinois) positioned vertically downward within a tripod at 175 cm (68.9 in) above the soil surface. One hour-long rainfall simulations were conducted on 1 m^2 (10.8 ft^2) circular runoff plots, first under antecedent moisture conditions (hereafter referred to as "dry run") and then about 24 hours later at field capacity (hereafter referred to as "wet run"). In tests prior to our research, three rainfall simulation tests per treatment showed that a rainfall application rate below 14 cm hr^{-1} (5.5 in hr^{-1}) would not likely produce runoff on the control treatment. Average rainfall application for the dry runs was 14.5 cm hr^{-1} (5.7 in hr^{-1}), which was the minimum rate that consistently produced runoff on all plots under antecedent soil moisture. After the dry run, plots were covered with plastic to prevent evaporation and ensure soils were at field capacity prior to wet runs. Average rainfall application for the wet runs was 14.9 cm hr^{-1} (5.9 in hr^{-1}). The two rainfall simulations on ten plots under three treatments yielded a total of 60 rainfall simulations.

A circular metal ring bounded the area of each plot for measurement of rainfall, runoff, sediment yield, and soil moisture. Two rain gauges were installed near the center of the plot and rainfall was measured at five-minute intervals. The plot ring was installed into the ground until a small runoff tray was level with the soil surface. A level and ruler were used to measure slope of the plot. One end of a 1.5 m (4.9 ft) long hose was clamped to the spout of the runoff tray, and the other end was placed in a 9 L (2.4 gal) collection tank outside the simulator spray zone. This procedure ensured that overspray from the simulator was not collected as runoff. A small screen was installed over the runoff tray to prevent pine needles and small twigs from entering the runoff collection tank. Runoff volume was measured with a graduated cylinder at five-minute intervals beginning at the time of the first runoff. Infiltration was calculated as the difference between the amount of water applied and the amount of runoff collected. At the right outside center of the plot ring, a CS615® (Campbell Scientific, Logan, Utah) automated soil moisture probe was installed horizontally into the soil at a depth of 5 cm (2 in). Volumetric water content (volume of water/volume of soil) from the probe was recorded at one-minute intervals during rainfall simulations. Soil moisture change was calculated by subtracting the initial soil moisture reading from the final soil moisture reading. After each simulation was completed and all runoff collected, runoff was thoroughly agitated before taking a 1 l (1.06 qt) subsample that was filtered and dried to calculate total suspended sediment (g L^{-1}). Sediment yield (g m^{-2}) was calculated by multiplying total suspended sediment by the total runoff (L m^{-2}). Finally, for comparison to other studies, sediment yield was extrapolated to (kg ha^{-1}).

All times were calculated from time zero, which was the time at the beginning of simulated rainfall. Time to peak runoff was defined as the time from time zero until the time runoff reached its peak. Equilibrium runoff rates were calculated by averaging the 50 and 55 minute runoff rates. Equilibrium infiltration rates were calculated by averaging the 50 and 55 minute infiltration rates. Since runoff was measured at five-minute intervals after runoff started, there was a lag time between rainfall and runoff data. Therefore, runoff data were interpolated to the actual five-minute intervals starting from time zero.

Plot surface and soil data were collected using methods described in detail by Madrid (2005). Surface roughness was measured in each plot with a relief meter that contained 20 pins at 5 cm (2 in) spacing (Kincaid and Williams, 1966). A soil core 0 to 5 cm (0 to 2 in) in depth was taken next to each plot prior to rainfall simulations following the core method (Blake and Hartage, 1986) and stored in a labeled plastic bag to determine soil moisture (gravimetric antecedent moisture content), soil bulk density, organic matter, and soil texture. These soil samples were oven dried for 48 hours at 105°C (221°F) prior to weighing. Organic matter was analyzed following the Walkley-Black procedure (Nelson and Sommers, 1982). Average depth to rock was measured north to south and east to west, across plots at 5 cm (2 in) intervals with a piece of rebar for a total of 40 measurements per plot. The rebar was pushed into the soil until it was obstructed by cobbles or fractured bedrock. The research area has cobble sized rock fragments floating in organic soil just above the highly fractured limestone bedrock layer. Soil texture was determined by measuring particle size distribution with a LS230® (Beckman-Coulter, Fullerton, California) laser diffraction particle size analyzer. Soil samples were prepared for texture analysis by crushing soil, pouring soil through a 2 mm (0.08 in) sieve, and removing identifiable organic matter. Soil samples were then split to a 10 g (0.02 lb) representative sample. An additional soil sample was crushed, poured through a 2 mm (0.08 in) sieve, split, and treated for removal of organic matter following the oxidation method using sodium hypochlorite (Anderson, 1961).

Along with soil measurements, vegetation data were collected to confirm the expectation that differences in infiltration, runoff, and sediment yield were due to treatment effects and not differences in site characteristics. Basal area of trees was measured with a ten-factor prism following the point-sampling method (Avery and Burkhart, 1994). The prism was centered over runoff plots to measure basal area of trees in a variable plot surrounding each runoff plot. Crown closure was measured with a spherical densiometer (Lemmon, 1956). Three transects were placed parallel across the 1 m^2 (10.8 ft^2) plot rings, and a measuring tape was used to measure ground cover, basal cover, and areal cover of grasses, forbs, and shrubs following the line intercept method (Elzinga et al., 2001). After wet runs, litter depth (including both litter and humus layers) was measured with a ruler perpendicular then parallel to the slope 1/4, 1/2, and 3/4 of the way across plots. All litter from the 1 m^2 (10.8 ft^2) plot was collected in a burlap sack and dried for five days at 70°C (158°F) prior to weighing to yield litter mass per unit area (kg m^{-2}). Grasses and forbs were clipped to the soil surface, collected in paper bags, oven dried for 48 hours at 70°C (158°F), and weighed to yield mass per unit area (kg ha^{-1}).

Data were analyzed using one-way nonparametric analysis of variance (ANOVA). Because side-by-side box and whisker plots indicated that data were not normally distributed, treatments were compared using the Kruskal-Wallis test (Ramsey and Schafer, 2002). In the presence of significant differences, post hoc analyses using the Wilcoxon test provided comparisons between pairs of sites. All analyses were conducted using SAS version 9.1® software (SAS Institute Inc, 2003). Significance was defined at $p \leq 0.05$ for both the Kruskal-Wallis and Wilcoxon tests.

Because forest stands had been selected post-harvest and plots were laid out along transects within stands, descriptive statistics and mixed models were used to assess the appropriateness of using a one-way analysis. Data were first analyzed to determine if random effects were present using Proc Mixed (SAS Institute Inc, 2003). Mixed models incorporating random effects for forest stands, transect, and both were compared to the fixed effects model. This analysis indicated that plots were independent of each other and confirmed the appropriateness of using the 1 m^2 (10.8 ft^2) plots as the experimental units in the one-way analysis. Using the one-way sampling design enabled us to perform nonparametric analysis. Medians are included in tables because, unlike means, they are resistant to outliers and skewness.

Results and Discussion

Based on one-way analyses, study sites were similar in regard to slope, herbaceous vegetation, and soils. Treatment areas did not differ in, slope, bare ground cover, rock cover, gravimetric antecedent moisture content, organic matter content, bulk density, or soil texture (Table 1).

Differences among treatments in runoff plots were found in tree basal area, crown closure, surface roughness, depth to rock, herbaceous biomass, herbaceous cover (basal and areal), litter cover, litter depth, and litter mass (Table 1). Tree basal area and crown closure were greater on the control site than on the pile and scatter sites. Surface roughness was greater on the scatter sites than on control or pile sites. Depth to rock was greatest on scatter sites followed by the pile sites and finally the control sites. Herbaceous biomass and herbaceous cover were greater on the pile and scatter sites than on control sites. Litter cover was greater on control sites than on pile and scatter sites. Litter depth was greater on control sites than on the scatter sites. Litter mass was greater on control and pile sites than on the scatter sites.

Differences in tree basal area and crown closure were expected because of thinning that took place on the pile and scatter treatment sites. However, there was only a small reduction in basal area and crown closure on the treated areas since only small diameter trees were harvested. The difference in surface roughness was also expected since plot rings were placed over residual slash, which was representative of the scatter treatment. The difference in herbaceous biomass and herbaceous cover was a result of almost no herbaceous plants occurring on the control sites. The control site contained no grasses and only a few forbs. Preliminary results from a concurrent vegetation response study suggest canopy closure on control sites contributes to lack of herbaceous growth, while more open canopies in silviculturally treated sites contribute to increased herbaceous growth (Mason et al., 2004). Results of herbaceous biomass and cover correspond to other studies that reported increases in herba-

Table 1. Site characteristics* for three forest silvicultural treatments in a mixed conifer forest near Cloudcroft, New Mexico.

	Treatment	Minimum	Median	Maximum	Mean	Standard deviation
Tree basal	Control[a]	27.6	45.9	55.1	45.7	8.4
Area	Pile[b]	20.7	32.1	41.3	31.5	7.4
(m^2 ha^{-1})	Scatter[b]	25.3	27.6	52.8	30.8	8.3
p-value*	0.0026					
Crown	Control[a]	77.0	95.5	98.0	92.1	6.9
Closure	Pile[b]	74.0	88.0	91.0	86.4	5.6
(%)	Scatter[b]	76.0	82.5	98.0	83.5	6.5
p-value	0.0188					
Slope	Control[a]	17	19	25	20	2
(%)	Pile[a]	18	22	27	22	3
	Scatter[a]	18	19	23	20	2
p-value	0.1365					
Grass	Control[a]	0	0	0	0	0
Biomass	Pile[b]	11.1	30.9	68.1	28.9	17.4
(kg ha^{-1})	Scatter[b]	0	12.3	45.1	16.9	13.9
p-value	< 0.0001					
Forb	Control[a]	0	0	64.1	7.4	20.1
Biomass	Pile[b]	0	11.9	65.5	18.5	19.2
(kg ha^{-1})	Scatter[b]	0	13.9	38.0	16.2	12.8
p-value	0.0196					
Grass	Control[a]	0	0	0	0	0
Basal Cover	Pile[b]	0	3.0	16.3	3.9	4.7
(%)	Scatter[b]	0.7	1.8	3.0	1.9	0.9
p-value	< 0.0001					
Forb	Control[a]	0	0	0.3	0	0.1
Basal Cover	Pile[b]	0	3.5	20.3	4.7	6.1
(%)	Scatter[b]	0.7	4.2	7.0	4.2	2.2
p-value	0.0005					
Grass	Control[a]	0	0	0	0	0
Areal cover	Pile[b]	0	6.5	17.3	6.3	5.2
(%)	Scatter[b]	1.3	5.0	9.3	5.0	2.4
p-value	0.0002					
Forb	Control[a]	0	0	1.3	0.1	0.4
Areal cover	Pile[b]	0	2.0	5.0	2.3	1.9
(%)	Scatter[b]	1.0	4.3	12.7	5.6	4.1
p-value	0.0001					
Litter cover	Control[a]	99.7	100.0	100.0	99.9	0.1
(%)	Pile[b]	61.7	92.5	96.7	89.0	10.4
	Scatter[b]	90.3	93.5	98.0	93.9	2.3
p-value	< 0.0001					
Litter depth	Control[a]	2.8	4.0	4.9	3.9	0.7
(cm)	Pile[ab]	1.7	3.9	5.6	3.7	1.4
	Scatter[b]	1.7	2.8	3.2	2.6	0.5
p-value	0.0262					
Litter mass	Control[a]	4.9	7.8	9.6	7.6	1.6
(kg m^{-2})	Pile[a]	5.4	7.3	11.0	7.5	1.7
	Scatter[b]	4.3	5.9	8.0	5.8	1.2
p-value	0.0231					

Table 1 continued on following page

Table 1. Continued.

	Treatment	Minimum	Median	Maximum	Mean	Standard deviation
Bare ground	Control[a]	0	0	0	0	0
Cover	Pile[a]	0	0	2.0	0.2	0.6
(%)	Scatter[a]	0	0	0	0	0
p-value	0.3679					
Rock cover	Control[a]	0	0	0	0	0
(%)	Pile[a]	0	0	4.0	0.6	1.3
	Scatter[a]	0	0	0	0	0
p-value	0.1263					
Gravimetric	Control[a]	17.0	41.3	89.9	41.5	21.8
antecedent moisture	Pile[a]	13.8	40.6	69.1	41.4	16.1
Content (%)	Scatter[a]	14.4	38.4	61.7	38.1	14.9
p-value	0.9008					
Organic matter	Control[a]	4.4	9.0	17.2	8.9	3.5
(%)	Pile[a]	5.9	8.9	12.0	8.9	2.5
	Scatter[a]	5.9	8.5	13.2	9.0	2.5
p-value	0.9786					
Soil bulk	Control[a]	0.103	0.166	0.198	0.160	0.028
Density	Pile[a]	0.103	0.173	0.227	0.171	0.038
(g cc^{-1})	Scatter[a]	0.142	0.186	0.214	0.181	0.023
p-value	0.3003					
Surface	Control[a]	0.53	0.69	1.41	0.77	0.26
Roughness	Pile[a]	0.64	0.80	1.79	0.88	0.33
	Scatter[b]	3.37	4.39	9.35	5.18	2.06
p-value	<0.0001					
Depth to rock	Control[a]	3.8	7.4	10.9	7.3	2.3
(cm)	Pile[b]	7.5	9.7	13.8	10.4	2.1
	Scatter[c]	11.6	17.8	40.3	20.5	9.4
p-value	<0.0001					
Sand	Control[a]	47.9	63.2	68.5	60.6	7.2
(%)	Pile[a]	52.4	58.9	64.2	58.5	4.1
	Scatter[a]	45.0	55.7	62.0	55.0	5.7
p-value	0.1954					
Silt	Control[a]	27.9	33.0	46.6	35.0	6.3
(%)	Pile[a]	32.0	37.4	43.0	37.3	3.6
	Scatter[a]	34.1	39.7	49.7	40.5	5.2
p-value	0.1352					
Clay	Control[a]	3.4	4.0	6.1	4.4	1.1
(%)	Pile[a]	3.2	4.0	6.3	4.2	0.8
	Scatter[a]	3.7	4.4	5.3	4.5	0.6
p-value	0.2358					

*** n = 10 plots in each of the three treatments.**

[a,b] within a variable, sites sharing the same letter do not differ significantly at the 0.05 alpha level based on pairwise comparisons using the Wilcoxon test.

† P-values from the Kruskal-Wallis test.

Table 2. Precipitation*, runoff†, infiltration‡, and soil moisture§ characteristics from dry run simulated rainfall on 1 m² plots for three forest silvicultural treatments¶ in a mixed conifer forest near Cloudcroft, New Mexico.

	Treatment	Minimum	Median	Maximum	Mean	Standard deviation
Precipitation	Control[a]	11.3	13.6	21.8	14.4	3.0
Rate	Pile[a]	12.1	14.5	18.3	14.8	2.2
(cm hr^{-1})	Scatter[a]	11.5	15.0	22.7	15.4	3.1
p-value*	0.6068					
Time to peak	Control[a]	6.3	7.1	16.8	8.8	3.4
Runoff	Pile[b]	6.2	14.5	46.9	21.4	16.1
(min)	Scatter[b]	11.0	40.1	56.6	35.9	15.3
p-value	0.0023					
Equilibrium	Control[a]	0.005	0.150	3.240	0.599	1.000
Runoff rate	Pile[a]	0.096	0.679	2.280	0.797	0.677
(cm hr^{-1})	Scatter[a]	0.075	0.456	1.830	0.632	0.539
p-value	0.2173					
Equilibrium	Control[a]	10.8	13.0	18.7	13.8	2.6
Infiltration	Pile[a]	8.8	13.8	18.0	13.6	3.1
Rate (cm hr^{-1})	Scatter[a]	10.9	12.7	23.6	14.1	3.8
p-value	0.9846					
Soil moisture change	Control[a]	7.4	23.9	56.9	25.6	13.3
(%)	Pile[a]	24.9	31.1	48.7	33.9	7.2
	Scatter[a]	15.3	28.0	49.3	29.8	9.1
p-value	0.0614					

* Precipitation was measured with two rain gauges at five-minute intervals.

† Runoff was measured with a graduated cylinder at five-minute intervals.

‡ Infiltration was calculated as the difference between the amount of water applied and the amount of runoff collected.

§ Soil moisture was measured with automated soil moisture probes at one-minute intervals.

¶ n = 10 plots in each of the three treatments.

a,b within a variable, treatments sharing the same letter do not differ significantly at the 0.05 alpha level based on pairwise comparisons using the Wilcoxon test.

** P-values from the Kruskal-Wallis test.

ceous vegetation following forest thinning (Cooper, 1960; McConnell and Smith, 1965; Jameson, 1967; Grelen et al., 1972). Studies have shown that several growing seasons are required for herbaceous plants to fully respond to silvicultural treatments (McConnell and Smith, 1965). Subsequent studies are planned to monitor herbaceous vegetation for several years to determine silvicultural treatment effects.

We were able to use both dry and wet run data for analysis of treatment effects. If gravimetric antecedent moisture content had differed significantly prior to dry run rainfall simulations, it would have been difficult to determine if runoff differences between plots were due to treatment effects or to differences in antecedent moisture content. However, gravimetric antecedent moisture content was relatively high throughout the study period due to ongoing natural rainfall and low evaporation conditions. Consequently, soil moisture prior to dry runs did not differ greatly among plots, and there were no significant differences in gravimetric antecedent moisture content prior to dry runs (Table 1).

During both dry and wet runs there was no difference among treatments in precipitation rates, equilibrium runoff rates, equilibrium infiltration rates, or soil moisture change (Tables 2, 3). During dry runs there was no difference in sediment yield among treatments (Table 4).

Differences among treatments were found in time to peak runoff for both dry and wet runs and in sediment yield for wet runs. Time to peak runoff was greater on pile and scatter sites (dry run medians = 14.5 and 40.1 min, wet run medians = 17.4 and 27.2 min) than on the control site (dry run median = 7.1 min, wet run median = 7.8 min) (Tables 2, 3). It is unlikely that differences in depth to rock affected timing of runoff since the soil horizon consisted of mineral soil, cobble sized rock interspersed with soil, and bedrock. Even with a shallow depth to rock, water was able to percolate into soil between the cobble-sized rocks, and shallow depth to rock did not affect runoff as shallow impermeable bedrock would have. During wet runs there was a difference in sediment yield with greater sediment yield on pile and scatter sites (medians = 0.828 and 0.897 kg ha^{-1}) than on control sites (median = 0.359 kg ha^{-1}) (Table 4).

Differences in runoff and infiltration rates were expected, but no differences were apparent among treatments. Our study contrasts with studies that indicate ground disturbance caused by forest management activities reduces infiltration rates and results in increased runoff (MacDonald and Stednick, 2003). While few studies were

Table 3. Precipitation*, runoff†, infiltration‡, and soil moisture§ characteristics from wet run simulated rainfall on 1 m^2 plots for three forest silvicultural treatments¶ in a mixed conifer forest near Cloudcroft, New Mexico.

	Treatment	Minimum	Median	Maximum	Mean	Standard deviation
Precipitation	Control[a]	11.0	13.8	19.4	14.4	2.9
Rate	Pile[a]	10.9	13.3	17.5	13.8	2.5
(cm hr^{-1})	Scatter[a]	12.1	16.7	20.6	16.4	2.9
p-value**	0.2897					
Time to peak	Control[a]	6.5	7.8	53.0	14.8	15.4
Runoff	Pile[b]	7.1	17.4	51.6	26.1	16.8
(min)	Scatter[b]	7.3	27.2	58.1	31.8	18.7
p-value	0.0174					
Equilibrium	Control[a]	0.012	0.250	4.563	0.691	1.385
Runoff rate	Pile[a]	0.028	0.323	2.373	0.790	0.883
(cm hr^{-1})	Scatter[a]	0.093	0.764	3.039	0.918	0.921
p-value	0.2347					
Equilibrium	Control[a]	6.2	13.0	18.7	13.6	3.5
Infiltration rate	Pile[a]	8.9	12.9	17.3	13.1	3.0
(cm hr^{-1})	Scatter[a]	11.0	14.3	23.0	15.6	4.3
p-value	0.4005					
Soil moisture change	Control[a]	6.4	16.8	23.4	16.7	5.2
(%)	Pile[a]	9.9	22.1	32.6	21.5	6.0
	Scatter[a]	2.9	16.4	27.2	16.2	7.6
p-value	0.1161					

* **Precipitation was measured with two rain gauges at five-minute intervals.**

† **Runoff was measured with a graduated cylinder at five-minute intervals.**

‡ **Infiltration was calculated as the difference between the amount of water applied and the amount of runoff collected.**

§ **Soil moisture was measured with automated soil moisture probes at one-minute intervals.**

¶ **n = 10 plots in each of the three treatments.**

a,b **within a variable, treatments sharing the same letter do not differ significantly at the 0.05 alpha level based on pairwise comparisons using the Wilcoxon test.**

** **P-values from the Kruskal-Wallis test.**

Table 4. Sediment yield* from simulated rainfall on 1 m^2 plots for three forest silvicultural treatments† in a mixed conifer forest near Cloudcroft, New Mexico.

	Treatment	Minimum	Median	Maximum	Mean	Standard deviation
Dry run	Control[a]	0.31	0.78	3.21	1.12	0.91
Sediment yield	Pile[a]	0.92	1.43	8.15	2.26	2.19
(kg ha^{-1})	Scatter[a]	0.10	1.91	3.14	1.77	0.93
p-value‡	0.1409					
Wet run	Control[a]	0.06	0.36	0.96	0.43	0.29
Sediment yield	Pile[b]	0.10	0.83	4.44	1.28	1.30
(kg ha^{-1})	Scatter[b]	0.30	0.90	1.77	0.95	0.45
p-value	0.0104					

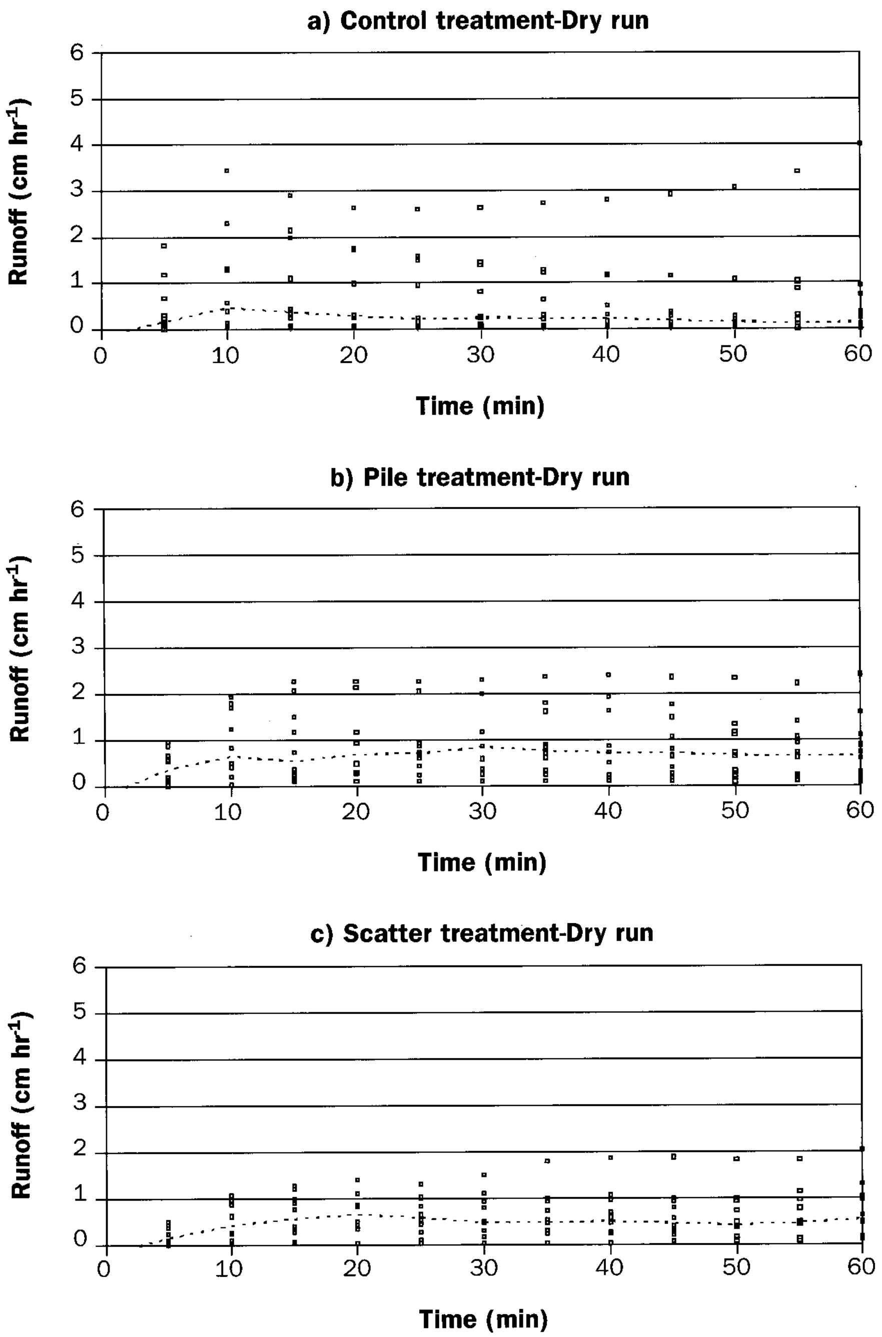
* **Sediment yield was filtered, dried, and weighed from a 1-L runoff subsample.**

† **n = 10 samples for each of the three treatments.**

a,b **within a variable, treatments sharing the same letter do not differ significantly at the 0.05 alpha level based on pairwise comparisons using the Wilcoxon test.**

‡ **P-values from the Kruskal-Wallis test.**

Figure 1
Dry run median runoff hydrographs for (a) control, (b) pile, and (c) scatter silvicultural treatments. Each rectangle represents an actual value at a time. The median value is plotted as a dashed line due to overlapping values.



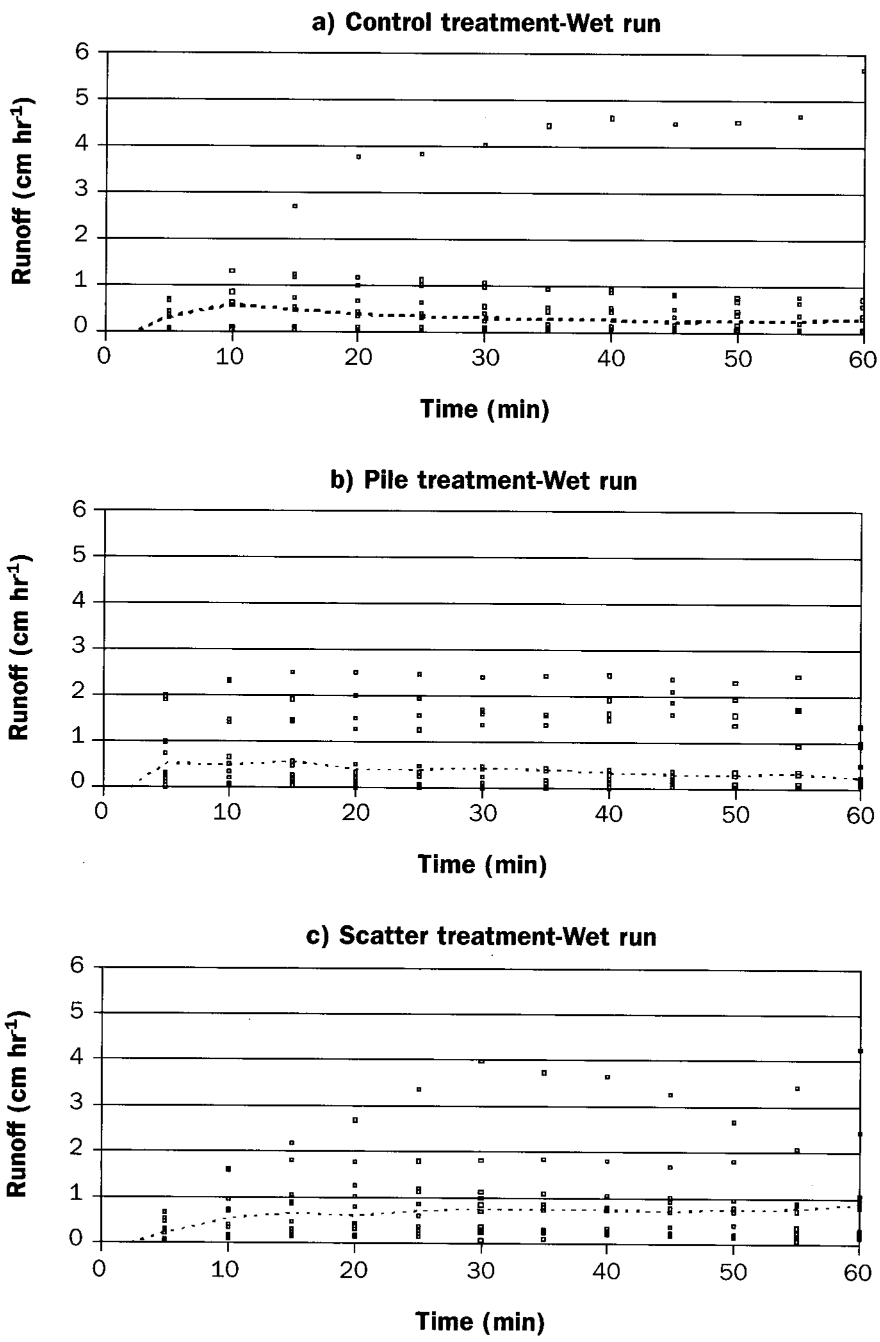
found that quantified infiltration rates in mixed conifer forest types, two rainfall simulation-type studies were found that showed a range of infiltration rates. Infiltration for ponderosa sites with scattered mixed conifer in Colorado ranged from 2.0 to 3.5 cm hr^{-1} (0.8 to 1.4 in hr^{-1}) (Benavides-Solorio and MacDonald, 2001), while infiltration under mixed conifer in northern New Mexico was > 26 cm hr^{-1} (10.2 in hr^{-1}) (Martin and Moody, 2001). In line with our study results, a study in ponderosa forests found that rainfall simulations did not produce runoff or sediment in the first year after tree harvest (Williams and Buckhouse, 1993). Runoff rates did not differ significantly, but time to peak runoff did differ among treatments (Tables 2, 3). Median runoff hydrographs illustrate the difference in time to peak runoff for both dry and wet runs (Figures 1 and 2). For both dry and wet runs, time to peak runoff was reached quickly in about 10 minutes on the control treatment, while time to peak runoff was delayed on pile and scatter treatments. Median runoff hydrographs show that runoff patterns were similar for both dry and wet runs (Figures 1 and 2).

Differences in sediment yield were expected since there was some site disturbance during thinning. However, significant sediment yield differences among treatments were only present during wet runs. Median sediment yield during dry runs was 0.78 kg ha^{-1} for control treatment, 1.43 for pile treatment, and 1.91 for scatter treatment (Table 4). Corresponding sediment yield during wet runs was 0.36 kg ha^{-1} for control treatment, 0.83 for pile treatment, and 0.90 for scatter treatment (Table 4). Wet-run results correspond with other studies that have also reported greater sedimentation following forest management (Stednick, 2000; MacDonald and Stednick, 2003; USFS, 1981). Generally, dry runs yielded greater sediment than wet runs. Out of 10 plots per treatment, dry-run sediment yield was greater than wet run sediment yield on eight control plots, 10 pile treatment plots, and seven scatter treatment plots.

Although sediment yield was statistically different and greater on pile and scatter treatments than the control treatment during wet runs, it was still very low. Studies have reported that undisturbed forest watersheds have erosion rates from near 0 to 560 kg ha^{-1} (0 to 0.25 t ac^{-1}) yr^{-1} (Binkley and Brown, 1993). Median values for sediment yield from dry and wet runs for pile and scatter treatments were below 2 kg ha^{-1} (0.0009 t ac^{-1}) (Table 4) for two, one-hour storm events with a rainfall intensity of 14.5 cm hr^{-1} (5.7 in hr^{-1}) and 14.9 cm hr^{-1} (5.9 in hr^{-1}). Considering the simulated storm events, total precipitation, and precipitation intensity, sediment yield was very low. We applied 25 percent of the average annual precipitation and measured less than 2 kg ha^{-1} (0.0009 t ac^{-1}) of sediment. Sediment yield amounts were very low compared to other studies that have found increases in sediment yield from 673 to 7,846 kg ha^{-1} (0.3 to 3.5 t ac^{-1}) following forest management (Grace, 2004).

Figure 2

Wet run median runoff hydrographs for (a) control, (b) pile, and (c) scatter silvicultural treatments. Each rectangle represents an actual value at a time. The median value is plotted as a dashed line due to overlapping values.



Limited sediment yield was probably due to the slight amount of ground disturbance during thinning and the great amount of litter that provided cover to the forest soil.

Without apparent differences in runoff or infiltration rate, differences in time to peak runoff were not expected, so additional statistical analyses were conducted to determine if these differences were due to differences in site characteristics. These analyses were also conducted for sediment yield to ensure that differences resulted from a treatment effect. Analysis of covariance (ANCOVA) -type regressions that incorporated a quantitative regressor along with site were used to control for individual site characteristics when assessing whether time to peak runoff and sediment yield were associated with treatments. These analyses suggested that time to peak runoff and sediment yield were significantly associated with treatment groups even when controlling for individual site characteristics. While a few site characteristic variables were significantly associated with the response, their inclusion in the analysis did not lead to a change in the pattern of significance among the treatment groups. Consequently, time to peak runoff and sediment yield differences among treatment groups are not explained by any other single site characteristic variable considered in this study.

Summary and Conclusion

Counter to our hypotheses, infiltration rates, runoff rates, and soil moisture content did not differ among treatments. However, pile and scatter treatment plots had a higher time to peak runoff, and in keeping with our hypothesis, had greater sediment yield than did the control treatment plots. Time to peak runoff was greater on pile and scatter treatments than on the control treatment during dry and wet runs. During dry runs, sediment yield did not differ among treatments. During wet runs, sediment yield was greater on pile and scatter treatments than on the control treatment. However, sediment yield was low compared to other published studies.

Results of this project provide land and water managers with scientific information that may help them in selecting silvicultural treatments that will reduce forest density without adversely affecting water quality. Based on data from this study, land and water managers using pile and scatter precommercial silvicultural treatments in mixed conifer forests might expect to obtain infiltration rates and runoff amounts similar to pretreatment levels with a small increase in sediment yield.

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References Cited

Allen, C.D. 1994. Linking ecology, GIS, and remote sensing to ecosystem management. Chapter 8, *In:* Remote sensing and geographic information systems in Ecosystem Management. A.V. Sample (ed.) Island Press, Covelo, California.

Allen, C.D., R. Touchan, and T.W. Swetnam. 1995. A landscape-scale fire history study supports fire management actions at Bandelier National Monument. Park Science Summer:18-19.

Anderson, J.U. 1961. An improved pretreatment for mineralogical analysis of samples containing organic matter. Clays and Clay Minerals 10:380-88.

Avery, T.E. and H. E. Burkhart. 1994. Forest measurements. McGraw-Hill, New York, New York.

Benavides-Solorio, J. and L.H. MacDonald. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydro Processes 15:2931-2952.

Binkley, D. and T. Brown. 1993. Forest practices as nonpoint sources of pollution in North America. Water Resources Bulletin 29:729-40.

Blake, G.R. and K.H. Hartage. 1986. Bulk density. Pp.363-375. *In:* Methods of soil analysis part 1-physical and mineralogical methods, second edition. A. Klute (ed.) Agronomy Society of America and Soil Science Society of America, Madison, Wisconsin.

Bosch, J.M. and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55:3-23.

Cooper, C.F. 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. Ecological Monographs 30:129-64.

Cram, D.S., T.T. Baker, J. Boren, and C. Edminster. 2003. Inventory and classification of wildland fire effects in silvicultural treated vs. untreated forest stands of New Mexico and Arizona. Second International Wildland Fire Ecology and Management Congress, presentation and full-length proceedings article, Orlando, Florida.

Dieterich, J.H. 1980. Chimney Spring forest fire history. Research Paper No. RM-220. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 8 pp.

Elzinga, C.L., D.W. Salzer, and J.W. Willoughby. 2001. Measuring and monitoring plant populations. Technical Reference No. 1730-31. U.S. Department of Agriculture Bureau of Land Management, National Business Center, Denver, Colorado.

Grace, J.M. 2004. Soil erosion following forest operations in the Southern Piedmont of central Alabama. Journal of Soil and Water Conservation 59(4):160-166.

Grelen, H.E., L.B. Whitaker, and R.E. Lohrey. 1972. Herbage response to precommercial thinning in direct-seeded slash pine. Journal of Range Management 25:435-37.

Jameson, D.R. 1967. The relationship of tree overstory and herbaceous understory vegetation. Journal of Range Management 20:247-49.

Kincaid, D.R. and G. Williams. 1966. Rainfall effects on soil surface characteristics following range improvement treatments. Journal of Range Management 19:346-51.

Lemmon, P.E. 1956. A spherical densiometer for estimating forest overstory density. Forest Science 2:314-20.

MacDonald, L.H. and J.D. Stednick. 2003. Forests and water: A state-of-the-art review for Colorado. Colorado Water Resources Research Institute Completion Report No. 196. Colorado Water Resources Research Institute, Fort Collins, Colorado. 65 pp.

Madrid, A. 2005. Evaluation of silvicultural treatment effects on infiltration, runoff, and sediment yield in a mixed conifer New Mexico forest. M.S. Thesis, New Mexico State University, Las Cruces, New Mexico. 135 pp.

Martin, D.A. and J.A. Moody. 2001. Comparison of soil infiltration rates in burned and unburned mountainous watersheds. Hydrology Proccesses 15:2893-2903.

Mason, G., T.T. Baker, J. Boren, D. Cram, B. Hurd, and C. Edminster. 2005. Fuel loading and vegetative response of mixed conifer stands to different types and frequencies of silvicultural treatment. Society for Range Management, poster presentation including abstract, January 10-12, 2005. Albuquerque, New Mexico.

McConnell, B.R. and J.G. Smith. 1965. Understory response three years after thinning pine. Journal of Range Management 18:129-132.

Nelson, D.W. and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. Pp. 539-580. *In:* Methods of soil analysis, Part 2. Chemical and microbiological properties, second edition. A.L. Page, R.H. Miller, and D.R. Keeney (ed.) Agronomy Society of America and Soil Science Society of America, Madison, Wisconsin.

National Oceanic and Atmospheric Administration (NOAA). 2003. Point precipitation frequency estimates. National Oceanic and Atmospheric Administration, Cloudcroft Ranger Station observing site. Available from: http://hdsc.nws.noaa.gov/hdsc/pfds/sa/nm_pfds.html.

Oliver, W.W. and R.A. Ryker. 1990. Pinus ponderosa Douglas Ex Laws: Ponderosa pine. Pp. 413-424. *In:* Silvics of North America, Volume 1. R.M. Burns and B.H. Honkala (ed.) Agriculture Handbook No. 654. U.S. Department of Agriculture Forest Service, Washington, D.C.

Ramsey, F.L. and D.W. Schafer. 2002. The statistical sluth: A course in methods of data analysis, second edition. Duxbury Press, Pacific Grove, California. 742 pp.

SAS Institute, Inc. 2003. SAS OnlineDoc® 9.1. SAS Institute Inc. Cary, North Carolina.

Stednick, J.D. 1996. Monitoring the effects of timber harvest on annual water yield. Journal of Hydrology 176:79-95.

Stednick, J.D. 2000. Timber management. Pp. 103-09. *In:* Drinking water from forest and grasslands: A synthesis of the scientific literature. U.S. Department of Agriculture Forest Service, Southern Research Station, GTR-39.

Swetnam, T.W. 1990. Fire history and climate in the southwestern United States. General technical report RM - Rocky Mountain Forest and Range Experiment Station, U.S. Department of Agriculture Forest Service 191:6-17.

Swetnam, T.W. and C.H. Baisan. 1996. Historical fire regime patterns in the southwestern United States since AD 1700. Pp. 11-32. *In:* Fire effects in southwestern forests. Proceedings of the Second La Mesa Fire Symposium, Los Alamos, New Mexico, U.S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Swetnam, T.W. and J.L. Betancourt. 1990. Fire-southern oscillation relations in the southwestern United States. Science 249:1017-20.

Touchan, R., T.W. Swetnam, and H.D. Grissino-Mayer. 1995. Effects of livestock grazing on pre-settlement fire regimes in New Mexico. General Technical Report INT 320:268-72.

Trimble, S.W. and F.H. Weirich. 1987. Reforestation reduces streamflow in the southeastern United States. Journal of Soil and Water Conservation 42(4):274-276.

U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS). 2003. Ecological site description. Available from: http://efotg.nrcs.usda.gov/references/public/NM/r039xc 051nm.pdf.

U.S. Department of Agriculture Forest Service (USDA-FS). 1981. Guide for predicting sediment yields from forested watersheds. USDA Forest Service, Northern and Intermountain Regions, Missoula, Montana. 46 pp.

Weaver, H. 1951. Fire as an ecological factor in the southwestern ponderosa pine forests. Journal of Forestry 49:93-98.

Weaver, H. 1964. Fire and management problems in ponderosa pine forests. Proceedings of the Annual Tall Timbers Fire Ecology Conference 3:60-79.

Williams, J.D. and J.C. Buckhouse. 1993. Winter logging and erosion in a ponderosa pine forest in northeastern Oregon. Western Journal of Applied Forestry 8:19-23.

Wilcox, B.P., M.K. Wood, J.T. Trimble, and T.J. Ward. 1986. A hand-portable single nozzle rainfall simulator designed for use on steep slopes. Journal of Range Management 39:375-77.