

Slash Treatment Greatly Reduces Sediment Yield from a Rapidly Eroding Piñon-Juniper Woodland

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ABSTRACT

The semi-arid piñon-juniper (*Pinus edulis* Engelm. and *Juniperus monosperma* [Engelm.] Sarg.) woodlands of Bandelier National Monument are experiencing accelerated erosion. Earlier studies suggest that causes of this rapidly eroding woodland are related to an unprecedented rapid transition of ponderosa pine savanna to piñon-juniper woodland as a result of cumulative historical effects of overgrazing, fire suppression, and a severe drought in the 1950's. To study the effectiveness of slash treatment in reducing erosion in degraded piñon-juniper woodlands, we utilized sediment check dams to quantify sediment yield from 12-paired microwatersheds (300-1100 m²) within an existing paired watershed study. Six of the 12 microwatersheds were located in a 41-ha (treatment) watershed with scattered slash treatment, and the other 6 microwatersheds were located in an adjacent 35-ha untreated (control) watershed. The primary purpose of our research was to quantify the rates of sediment yield between the treated and control microwatersheds. Sediment yield was measured from 15 individual storms during the months of June-September (2000 and 2001). Mean seasonal sediment yield was reduced 2 orders of magnitude in response to the slash treatment (In 2000: 2,988 kg/ha control vs. 31 kg/ha treatment; In 2001: 2,069 kg/ha control vs. 71 kg/ha treatment).

The practice of slash treatment in degraded piñon-juniper woodlands is providing encouraging evidence of its efficacy in reducing erosion in Bandelier National Monument by encouraging herbaceous recovery in intercanopy areas. Our data show that the slash treatment increases total ground cover—slash and herbaceous growth—beyond a potential erosion threshold. Restored piñon-juniper woodlands, as the result of slash treatment, provide a forest structure similar to pre-grazing and pre-fire suppression conditions and a decreased catastrophic fire hazard.

INTRODUCTION

In the Southwest, piñon-juniper (*Pinus edulis* Engelm. and *Juniperus monosperma* [Engelm.] Sarg.) woodlands have expanded dramatically during the last century, increasing in both areal extent and density. In New Mexico alone, piñon-juniper woodlands cover an area of 6 million hectares (Mitchell and Roberts 1999).

Bandelier National Monument and the adjacent Santa Fe National Forest in north-central New Mexico have documented thousands of hectares with degraded piñon and juniper communities (Jacobs and Gatewood 1999). Loss of soil resources threatens the ability to restore and sustain pre-erosion plant communities of native rangeland species. Furthermore, Bandelier National Monument was created in 1916 as a unit of the National Park Service (NPS) to protect and preserve ancestral Puebloan cultural remains and the wilderness ecosystem that contains them. Today, the greatest threat to both these natural and cultural resources is accelerated erosion in the piñon-juniper woodlands.

An unprecedented shift in piñon-juniper community structure has resulted from the

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cumulative, historical effects of overgrazing, fire suppression, and a severe drought in the 1950's (Davenport et al. 1998, Wilcox et al. 1996a, Jacobs and Gatewood 1999, Gottfried et al. 1995, Allen 1989). Based on local fire history, piñon-juniper age class structure, and soils data, there is evidence to support that fire sensitive piñon-juniper woodlands became established in areas formerly occupied by open grassland, mixed woodland, and/or ponderosa pine savanna communities (Allen 1989). At the lower elevation limit of the ponderosa pine savanna communities in Bandelier National Monument (1900-2100 m), these former communities included well-developed soils and herbaceous understories that protected the soil from rapid erosion and provided a largely continuous fuel matrix which allowed surface fires to spread and maintain these communities (Sydoriak et al. 2000).

Sheep and cattle grazing were a large component of this region since the introduction of the railroad in the early 1880's, and were not eliminated from Bandelier National Monument until 1932. However, feral burros continued to cause widespread effects on the herbaceous understory and soil impacts through most of the 20th century, until they were eliminated from Bandelier National Monument by 1980 (Allen 1989).

Fire suppression initiated by the federal government in the early 1900's (Sydoriak et al. 2000) further degraded the integrity of the ecotone between ponderosa pine savanna and piñon-juniper woodlands. Finally, a severe drought documented throughout the southwest during the 1950's exacerbated competition for soil moisture with the woodland understory and resulted in the mortality of large communities of ponderosa pine (Allen and Breshears 1998). Cumulatively, these impacts provided the opportunity for fire-sensitive, more drought resistant piñon and juniper to become established in densities unprecedented for at least the past 800 years (Allen 2001, Julius 1999).

Soil and nutrient resources are rapidly being removed by accelerated erosion

(Davenport et al. 1998). A large component of the Bandelier Wilderness is composed of dense areas of overstocked young piñon and juniper trees and intercanopy spaces lacking an effective ground cover due to the competitive nature of piñon and juniper for soil water resources. Intercanopy soils are exposed to rainfall erosivity and overland flow generated from intense monsoon season thunderstorms. Limited ground cover causes soil to be susceptible to rainsplash erosion causing soil compaction, reducing infiltration, and converting a larger proportion of the rainfall directly into overland flow. Runoff coefficients in piñon-juniper woodland studies on the Pajarito Plateau have been measured to exceed 40% during the summer (Wilcox 1994).

Unprotected soil in the intercanopy areas is also exposed to intense heating between storms, causing increased evaporation, reducing soil moisture, and creating a harsh microclimate that limits the successful establishment of new herbaceous plants (Jacobs and Gatewood 1999). These conditions, could jeopardize the long-term ecological productivity and stability of the ecosystem.

In addition, these conditions and processes exacerbate the risk of permanent loss of cultural artifacts, ultimately degrading the cultural resources Bandelier National Monument was established to protect. In another study within Bandelier National Monument, Allen (2001) has quantified as many as 1,040 cultural artifacts moved by a single rainfall-runoff event into a sediment trap draining only 1 hectare on a gentle (5%) hillslope. Provenance is of utmost importance for archeologists; if the original location of an artifact cannot be determined, its scientific significance is greatly diminished. Bandelier National Monument has over 2,500 surveyed archeological sites scattered over 13,629 hectares with as much as 35% of that area still unsurveyed (R. Gauthier, Park Archeologist, personal communication, 2001).

In the absence of cattle and sheep grazing for 68 years, the ecological system

has not reverted back or regained functionality relative to pre-grazing status, which may suggest that the factors and processes perpetuating this present state may require management intervention (Jacobs et al. 2000). In recognition that the degraded condition of the understory was the primary cause of accelerated erosion, in 1996 the National Park Service (NPS) initiated the Bandelier Watershed Restoration Project to validate positive results of previous small-scale plot studies utilizing slash treatment (the mechanical thinning of piñon-juniper and subsequent scattering of stems and branches over intercanopy areas).

The purpose of this research was to quantify the differences in sediment yields between treated and untreated areas. The extent that slash treatment is effective in reducing sediment yield will help determine whether slash treatment is appropriate for restoring piñon-juniper ecosystems at the park level and perhaps for consideration on other public lands in the western United States with similar land use histories and problems.

PREVIOUS RESEARCH

Multiple runoff and erosion studies have been conducted across piñon-juniper woodlands on the Pajarito Plateau of north-central New Mexico (Wilcox et al. *in press*, Allen 2000, Davenport et al. 1998, Reid et al. 1999, Wilcox 1994, Wilcox et al. 1996a, b). After 9 years of data collection from a multiple scale experimental watershed study, it has been observed that degraded piñon-juniper woodlands of Bandelier National Monument are experiencing accelerated erosion rates of up to 10,000 kg/ha/year (C. Allen, personal communication, 2002).

Wilcox et al. (1996b) examined the effect of 11 convective thunderstorms on sediment yield from small plots on tuff-derived sandy loam soils within bare-intercanopy areas and canopy areas in degraded piñon-juniper woodlands. They determined the intercanopy areas lost soil at

a mean annual rate of 3300 kg/ha (coefficient of variation = 69%) compared to canopy areas, which experienced sediment yield rates of 60 kg/ha (no replicates). Additional local studies conducted by Reid et al. (1999) and Wilcox et al. (*in press*) found convective thunderstorms rather than frontal storms to have greater influence on converting a large proportion of rainfall to overland flow and hence producing the highest sediment yield. Erosion is slight during the winter, even when runoff is high, because of less raindrop impact (Wilcox 1994). These studies allowed current and future studies in north-central New Mexico to focus on sediment yield/soil loss during the monsoon season.

Davenport et al. (1998) illustrated the tight linkages between herbaceous cover and hillslope erosion rates. In addition, they caution that some sites may have crossed an erosion threshold and will require intensive management to reduce accelerated erosion rates.

Several studies (Jacobs and Gatewood 1999, Javed 1991) have provided evidence that slash treatment can be effective in reducing soil loss and sustaining ecological integrity and productivity. Javed (1991) tested different treatments on reducing runoff and erosion in piñon-juniper woodlands of southeastern New Mexico and found that the subsequent scattering of slash thinned from individual trees provided the most benefits with reduced runoff and erosion and subsequent recovery of herbaceous cover. Initial studies in Bandelier National Monument (Jacobs and Gatewood 1999) showed substantial increases in grasses and forbs from overstory reduction by mechanical thinning and scattering of slash.

METHODS

Study Area

The study site is located in Bandelier National Monument in north-central New Mexico (35° 46' 25" N, 106° 16' 21" W) (Figure 1). Bandelier National Monument is situated on the Pajarito Plateau, a dissected

volcanic landscape of alternating mesas and canyons that is located on the east flank of the Jemez Mountains, draining southeasterly to the Rio Grande. The defining feature of the Plateau is the Tshirege Member (Miocene to early Pleistocene) of the Bandelier Tuff, a massive series of “ash-flow tuffs” commonly 30-100 m in thickness. These volcanics were erupted from the Jemez Mountains at ca. 1.22 MA and associated with development of the Valles Caldera (Reneau and McDonald 1996). It appears the

landscape was stable enough to allow significant soil development from tuff prior to the eruption and deposition of the pumice about 60,000 BP (Davenport 1997). The pumice is distributed across the study area with significant accumulations on the east and south facing slopes. The study site is located between 1950-1980 m. This elevation approaches the highest elevation limit (~2300 m) for piñon-juniper woodlands in New Mexico.

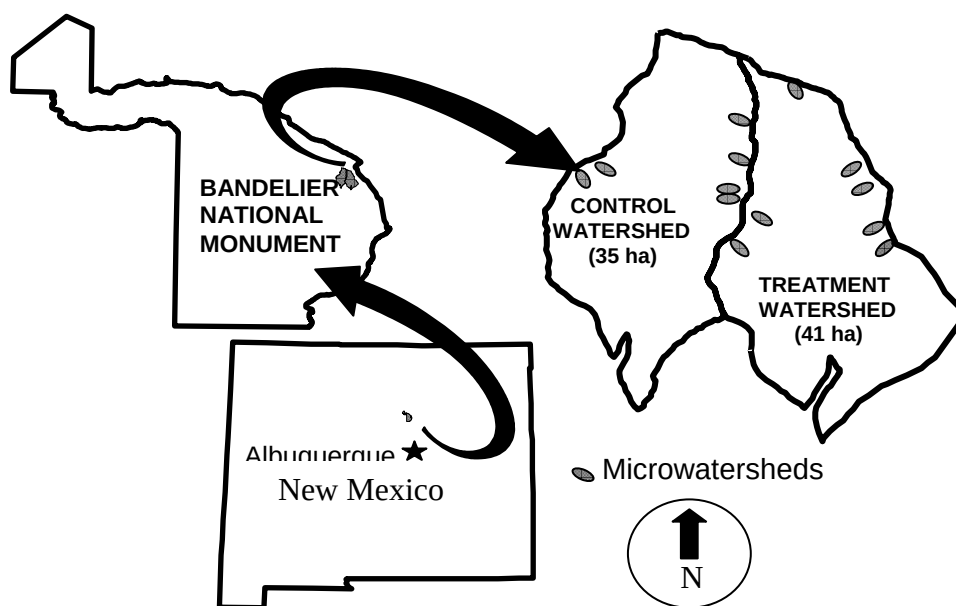


Figure 1. Location of study, Bandelier Watershed Restoration Project, Bandelier National Monument, New Mexico.

Climate

This region of New Mexico is subjected to a semiarid continental climate (Gottfried et al. 1995), where average annual air temperature ranges from -1.6°C in January to $+20^{\circ}\text{C}$ in July with mean annual precipitation of 427 mm (Bandelier National Monument 2001). The Southwestern Summer monsoon season, which most commonly starts at the beginning of July, is typically a weather period dominated by convective thunderstorm activity lasting

through September. Monsoon rains associated with this period are characterized by localized, high-intensity, short-duration rainfall. Total precipitation during these three months is generally 40%-60% of the total annual precipitation (Bowen 1996).

Experimental Design

The Bandelier Watershed Restoration Project is a paired watershed study designed to test the efficacy of a watershed-scale scattered slash (treatment) watershed, in comparison to an untreated

(control) watershed. The watersheds are adjacent and similar in size (treatment 35-ha, control 41-ha), geology, topography, soil type, and vegetation. Slash treatment was imposed on one of the two watersheds in 1996-1997. Trees less than 20 cm in diameter were cut, leaving larger trees to represent a structure similar to pre-grazing conditions (Jacobs et al. 2000). Piñon-juniper overstory canopy was reduced from 33% to 9%. Piñon cover was reduced from 15 to 4% and juniper from 18 to 5%, effectively maintaining the pretreatment cover ratio between the two species (Gatewood 1999). Slash was scattered across intercanopy areas and in existing rills and gullies.

For this study, comparisons between the treatment and control watersheds were conducted through replication of 6 microwatersheds (300-1100 m²) within each watershed. The small microwatersheds were delineated and surveyed with a Nikon DTM-420 Total Station survey unit and prism for high precision and accuracy of contributing areas.

The microwatersheds were replicated and paired, based on four criteria: (1) aspect; (2) slope position = upper 1/3 slope; (3) slope; and (4) soil type. Four replicates located on the west aspect of each watershed represent non-pumice soils. Two replicates located on the east aspect of each watershed represent pumice or pumice-derived soils.

Characterization of Soils and Vegetation
Davenport (1997) conducted an extensive and detailed soil survey of the study area, including both control and treatment watersheds. Julius (1999) simplified the soil survey into units comprising pumice and sandy loam components, present or absent of an argillic horizon. We excavated and analyzed soil pits where survey maps contradicted field observations for the study sites.

Site-specific soil bulk density samples were collected representing the two main soil types (pumice and non-pumice). Three

samples of each soil were obtained with minimal soil disturbance using a 230 mL aluminum canister with air holes to minimize compaction when collected. The 3 samples were weighed independently using an electronic precision scale (accuracy = 0.01 g).

Intercanopy ground cover was determined from transects conducted pre and post-growing season for 2000 and 2001. Five to seven transects were recorded along the contour, across the width of each microwatershed at equidistant intervals up the hillslope to accumulate approximately 100 data points for each microwatershed. The nature of the ground cover was recorded at 1-m intervals using these categories: bare soil; forb; grass; litter and/or slash.

Canopy cover was estimated from 1:800 scale, 1-m² resolution aerial photography (LANL 2000) of each microwatershed. A transparent dot-grid overlay with 10-dots per cm² allowed a systematic estimate of canopy versus intercanopy areas. The proportion of canopy cover was determined from the number of canopy points over the total number of points within each microwatershed. Canopy cover and other microwatershed characteristics, described above, are presented in Table 1.

Precipitation Measurements and Characteristics

Each microwatershed was instrumented with a 20.3 cm diameter, tipping bucket rain gage with 0.25 mm resolution (12 total rain gages). Precipitation data (total storm precipitation, duration, and intensity) were collected using HOBO data loggers with one-minute interval resolution (mm/min). For the purpose of this study an event was defined as a period of continuous rain separated from the following event by a time interval of 60 minutes. Precipitation records from the Bandelier National Monument climate station were used to compare long-term monthly precipitation averages and extremes during the study period. The station is located approximately 1000 m

Table 1. Bandelier Watershed Restoration Project microwatershed characteristics, 2000-2001.

Microwatershed	Control					
	1	2	3	4	5	6
area (ha)	0.086	0.055	0.032	0.071	0.078	0.034
hillslope length (m)	73	72	45	43	45.5	53
slope (%)	13	13	14	16	17	13
canopy cover (%)	55	33	49	57	49	63
ground cover [†] (%)	14/8	6/5	8/4	11/11	7/4	11/2
soil type [‡]	Inceptisol (non-pumice)	Inceptisol (non-pumice)	Alfisol (non-pumice)	Alfisol (non-pumice)	Andisol (pumice)	Andisol (pumice)
soil bulk density (g/cm ³)	1.26	1.21	1.43	1.30	0.60	0.96
Microwatershed	Treatment					
	1	2	3	4	5	6
area (ha)	0.072	0.097	0.063	0.076	0.103	0.132
hillslope length (m)	60.5	50.5	54	69	45	52
slope (%)	10	13	13	13	22	15
canopy cover (%)	11	26	12	28	20	21
ground cover [†] (%)	39/51	48/57	53/55	59/49	48/56	54/49
soil type [‡]	Inceptisol (non-pumice)	Alfisol (non-pumice)	Alfisol (non-pumice)	Alfisol (non-pumice)	Andisol (pumice)	Andisol (pumice)
soil bulk density (g/cm ³)	1.14	1.40	1.30	1.29	0.78	0.77

[†] average pre/average post growing seasons (June 2000-2001/ September 2000-2001)[‡] As described by Davenport 1997, Julius 1999

northeast of the study site at 1847 m in elevation with a 76-year record (1925-2001).

The highest 30-minute intensity (I_{30}) in mm/hr was obtained by using data output from HOBO data loggers for one minute-intensity data for each sediment yield-producing storm. Storm rainfall energy was calculated empirically using the 30-minute intensity data and Brown and Foster equation in Renard et al. (1997):

$$E = 0.29[1 - 0.72 \exp(-0.05I)],$$

where E is rainfall energy (MJ/ha/mm) and (I) is the 30-minute highest intensity (mm/hr).

The product of a storm's rainfall energy and intensity is defined as the rainfall erosivity, or the ability of rainfall to erode soil. Rainfall erosivity determined from the highest 30-minute intensity (EI_{30}) is strongly correlated to predicting sediment yield/soil loss in multiple studies (Brown and Foster 1987, Foster et al. 1982, Ulsaker and

Onstad 1984, and Wischmeier and Smith 1958), including the Revised Universal Sediment yield Equation (RUSLE) (Renard et al. 1997).

We calculated individual storm's rainfall erosivity (EI_{30}), in Newtons per hour (N/hr) for each sediment yield-producing storm using the above energy equation and the highest 30-minute rainfall intensity determined from one-minute resolution data for each rain gage.

Sediment Yield Measurements

Sediment check dams were constructed at the outlet of each microwatershed. The check dams measured between 1.8 – 3.7 m in length and up to 0.6 m in height and were constructed of welded wire mesh, covered with permeable geo-textile (silt fence), and secured into the ground with rebar. Check dam basin volumes ranged 0.18 – 0.25 m³ and basins were lined with 6-mm plastic

aprons to determine a base level. The basin aprons were secured to the soil

surface with 30 cm landscape staples at frequent intervals to reduce edge effects. Check dams included rectangular weir-like spillways to reduce erosion and scour around the dams during overflow events.

In two events, several microwatershed check dams in the control watershed were overtopped by runoff and sediment in the beginning of the study period. Subsequently, the control microwatershed check dams were enlarged to include storage capacities exceeding 0.5 m³. Data were insufficient for estimating sediment yields lost over the check dams. However, the author believes they were less than 10% of the total sediment yield.

Sediment yield was quantified by mass per unit area on a storm-by-storm basis for 2 seasons (2000-2001) from June-September. Sediment accumulations in each check dam were excavated and spread on a tarp to air dry for a period of a day or two after each rainfall-runoff event. The sediment was then placed in a bucket and weighed using a spring scale to the nearest 0.1 kilograms and adjusted for tare weight. Small accumulations of sediment were measured to the nearest gram. Contributing areas of each microwatershed were determined to the nearest 0.001 hectares (1 m²) from total station surveys data and Surfer[®] software. Mass of sediment per unit area (kg/ha) was calculated for each microwatershed per rainfall-runoff event.

RESULTS AND DISCUSSION

Storm Analysis

The total precipitation for the two, 4-month periods was below average for both years when compared to long-term averages (Figure 2). A total of 41 precipitation events (>1mm), including 1 frontal storm, were observed and recorded during the study period. Fifteen events generated runoff and measurable sediment yield from the scale of

study (Table 2). Mean convective storm rainfall totals generating runoff ranged from 2.9 mm to 30.5 mm of rain, and 64 mm for the frontal storm. Although the convective thunderstorms have low depths of precipitation, an intense period of each storm was recorded within a short time period, commonly less than 15 minutes. These short duration, high intensity storms are associated with high rainfall-erosivity, a significant component for sediment yield.

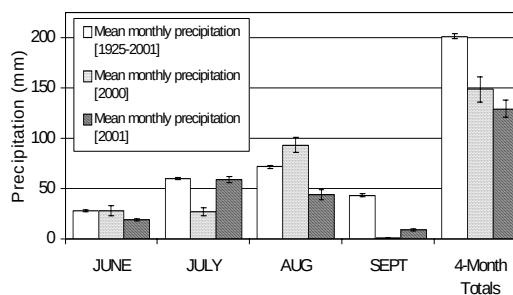


Figure 2. Study period precipitation (2000-2001) versus long-term average precipitation (1925-2001). Historical precipitation error bars represent one standard deviation with 76 years of data. Error bars for 2000-2001 data represents one standard deviation of 12 rain gages. June 2000 represents mean precipitation and standard deviation of 3 rain gages.

Table 2. Individual storm event characteristics recorded during the study period, 2000-2001.

Storm Date	Storm Type	Mean Total [†] Storm Precipitation (mm)	Highest [‡] 1-Minute Intensity (mm/hr)	Highest [‡] 30-Minute Intensity (mm/hr)	Highest [‡] Rainfall-Erosivity (EI ₃₀) (N/hr)
2000					
28-Jun	Convective	6.1 (17%) [§]	106.7	18.3	9.5 (23%)
17-Jul	Convective	2.9 (23%)	53.3	14.5	7.3 (73%)
25-Jul	Convective	7.0 (20%)	15.2	8.1	5.7 (38%)
29-Jul	Convective	8.4 (11%) [§]	61.0	19.6	10.6 (10%)
6-Aug	Convective	5.3 (22%) [¶]	91.4	14.7	7.2 (33%)
9-Aug	Convective	16.8 (12%)	167.6	38.6	25.5 (22%)
15-Aug	Convective	5.5 (17%)	76.2	12.7	5.8 (23%)
18-Aug	Frontal	65 (7%)	91.4	16.3	8.2 (18%)
2001					
19-Jun	Convective	10.4 (4%)	30.5	15.2	7.5 (9%)
2-Jul	Convective	30.5 (8%)	167.6	60.2	42.7 (12%)
14-Jul	Convective	4.9 (17%)	61.0	12.2	5.4 (23%)
1-Aug	Convective	6.6 (8%)	15.2	9.1	3.7 (15%)
10-Aug	Convective	8.7 (21%)	61.0	21.8	12.1 (32%)
12-Aug	Convective	9.5 (13%)	30.5	16.3	8.2 (22%)
16-Sep	Convective	6.7 (8%) [§]	61.0	14.7	7.1 (12%)

[†] Mean precipitation totals of 12 rain gages (coefficient of variation)

[‡] Highest value recorded/calculated from any 1 of 12 rain gages

[§] mean and coefficient of variation for 11 rain gages

[¶] mean and coefficient of variation for 10 rain gages

Sediment Yield

Sediment yield was quantified by individual rainfall-runoff events for the months of June, July, August, and September for two consecutive seasons. The treatment microwatersheds consistently exhibited mean total sediment yields two orders of magnitude less than the control microwatersheds for each season (Figure 3). In 2000, the 6 control microwatersheds exhibited a mean sediment yield of 2,988 kg/ha/season (3.0 tonnes/ha), whereas the 6 treated microwatersheds exhibited a mean sediment yield of only 31 kg/ha/season (0.03 tonnes/ha). In 2001, the 6 control microwatersheds exhibited a mean sediment yield of 2,069 kg/ha/season (2.1 tonnes/ha), whereas 6 treated

microwatersheds exhibited a mean sediment yield of 71 kg/ha/season (0.07 tonnes/ha). Table 3 lists sediment yields for both the control and treated microwatersheds in 2000 and 2001.

Table 3. Total seasonal sediment yields (kg/ha) in 2000 and 2001 for individual treatment and control microwatersheds.

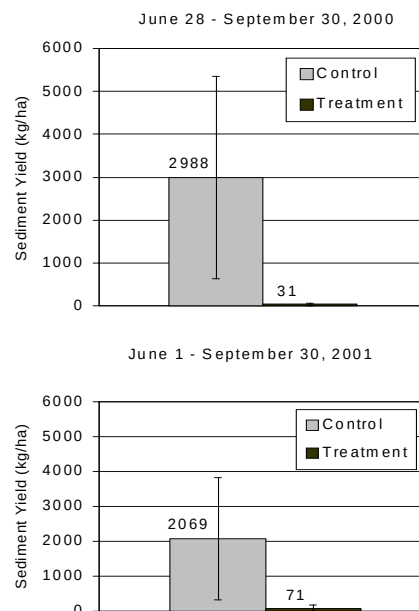


Figure 3. Seasonal sediment yields (kg/ha) for treatment (n=6) and control (n=6) microwatersheds, 2000-2001. Error bars represent one standard deviation.

2000							
Micro-watershed	Area (ha)	Soil Description	Sediment Yield (kg/ha)	Micro-watershed	Area (ha)	Soil Description	Sediment Yield (kg/ha)
<i>Control</i>				<i>Treatment</i>			
C1	0.09	Non-pumice	1736	T1	0.07	Non-pumice	15
C2	0.06	Non-pumice	2948	T2	0.10	Non-pumice	18
C3	0.03	Non-pumice	7278	T3	0.06	Non-pumice	97
C4	0.07	Non-pumice	3669	T4	0.08	Non-pumice	51
C5	0.08	Pumice	1758	T5	0.10	Pumice	1
C6	0.03	Pumice	540	T6	0.13	Pumice	3
2001							
Micro-watershed	Area (ha)	Soil Description	Sediment Yield (kg/ha)	Micro-watershed	Area (ha)	Soil Description	Sediment Yield (kg/ha)
<i>Control</i>				<i>Treated</i>			
C1	0.09	Non-pumice	2301	T1	0.07	Non-pumice	41
C2	0.06	Non-pumice	4071	T2	0.10	Non-pumice	53
C3	0.03	Non-pumice	4006	T3	0.06	Non-pumice	168
C4	0.07	Non-pumice	2410	T4	0.08	Non-pumice	198
C5	0.08	Pumice	75	T5	0.10	Pumice	7
C6	0.03	Pumice	37	T6	0.13	Pumice	4

Over the 2-season study, most of the total sediment yield resulted from a one or two large convective thunderstorms each season. On August 9, 2000, we recorded a mean of 16.8 mm of rain in less than an hour with a peak rainfall intensity of 167.6 mm/hr—calculated from one-minute data—and mean rainfall-erosivity of 25.5 N/hr. The storm resulted in 62% of the total seasonal sediment yield in the control microwatersheds and 43% of the total seasonal sediment yield in the treatment microwatersheds. On July 2, 2001, we recorded a mean of 26 mm of rain in less than 30-minutes with a peak rainfall intensity of 167.6 mm/hr and mean rainfall-erosivity of 42.7 N/hr. The July 2, 2001 storm resulted in 94% of the total seasonal sediment yield in the control microwatersheds and 81% of the total seasonal sediment yield in the treatment microwatersheds.

Limited information is available to determine the frequency of the magnitude of rainfall-erosivity from these storms. It has been suggested that most of the rainfall events observed in 2000-2001 have a recurrence interval equal to or less than 2

years while the July 2, 2001 storm may have a less frequent return period of between 2-10 years when compared to a 10-year analysis (Bowen 1996) of monsoon thunderstorm amounts at points approximately 6 km away and at a similar elevation to the study site.

A frontal storm on August 18-19, 2000 recorded more than three times the rainfall depth as the August 9, 2000 convective storm. However, the storm was characterized by low rainfall intensity, and therefore, low rainfall-erosivity values. The convective storm exhibited total sediment yield one order of magnitude more than the frontal storm, regardless of treatment or control microwatersheds. However, the frontal storm still produced a significant amount of seasonal sediment yield; 21% of the total seasonal sediment yield for the control microwatersheds and 14% of the total seasonal sediment yield for the treatment microwatersheds. Multiple frontal storms are typical during the late summer and autumn months in Bandelier National Monument.

Wischmeier and Smith (1958) studied numerous combinations of rainfall

characteristics, interaction effects, indices of antecedent moisture, and soil compaction for predicting sediment yield. The best single variable for sediment yield prediction was rainfall-erosivity (EI_{30}). In our study, a correlation analysis exhibited a moderately strong indication of rainfall-erosivity (EI_{30}) as the single variable controlling factor in sediment yield when examined separately for both the 6 control microwatersheds ($n = 90$, $r^2 = 0.48$), and the 6 treatment microwatersheds ($n = 90$, $r^2 = 0.37$). The data were transformed using natural logarithms.

We examined sediment yield associated with individual storm rainfall-erosivity values (EI_{30}). Rainfall erosivity was found to be the best single variable factor for the prediction of sediment yield in our study when compared to other single variables: amount of precipitation; rainfall energy; and rainfall intensity. Our data suggest slash treatment aids in reducing the impact of rainfall-erosivity on sediment yield (Figure 4). Variability associated with regressing rainfall erosivity and sediment yield was partially contributed by soil type (pumice vs. non-pumice soils). Sediment yield was found to differ significantly ($p < 0.001$) in response to soil type, regardless of treated or control. Therefore, soil types were further examined separately.

Sediment yield response to mechanical thinning and slash treatment was obvious, with treatment microwatersheds exhibiting sediment yields 1-3 orders of magnitude less than the comparable control microwatersheds, regardless of soil type. However, soil type was an important determinant of site erosivity. In 2000, non-pumice microwatersheds exhibited sediment yields 1-2 orders of magnitude more than pumice microwatersheds, irrespective of treatment effects (with the

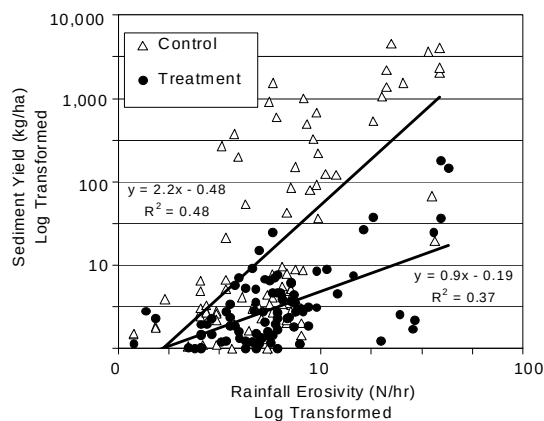


Figure 4. Effects of slash treatment on soil loss as a function of rainfall-erosivity, 2000-2001. Control: $n = 90$; Treatment: $n = 90$. Data are transformed using natural logarithm.

exception of C5 in 2000). In 2001, non-pumice microwatersheds experienced sediment yields 2 orders of magnitude greater than for pumice microwatersheds across treatment and control area. Table 3 illustrates sediment yields for each microwatershed for each season. Therefore, based on our data, we suggest the non-pumice soils (Inceptisols, Alfisols) have a high soil erosion hazard relative to pumice soils (Andisols). In fact, non-pumice soils in untreated (control) microwatersheds consistently exhibited seasonal sediment yields exceeding local soil survey annual tolerance levels of 2,200 kg/ha (Earth Environmental Consultants, Inc. 1974).

We suggest the reason for the significant differences in sediment yield between the non-pumice and pumice soils is texture. Although slash treatment on pumice soils still provides significant evidence that its application reduces excessive sediment yield, the texture and nature of these soils are extremely different than the non-pumice soils. The pumice soils consist of deep, well-drained soils developed from pumice and include a very gravelly loam texture (Davenport 1997). This texture is thought to provide increased infiltration rates and a reduced runoff

potential in most storms. Significant pumice soil movement was observed only in the highest rainfall-erosivity storm events within the 2-season study. Movement may occur in pulses when enough runoff is generated to float pumice due to its lower particle and bulk densities relative to the non-pumice soils.

The significant difference in sediment yield between the control and treatment microwatersheds, regardless of soil type, can be largely attributed to an increase in herbaceous ground cover in the treatment microwatersheds as a result of a change in the hillslope hydrological processes induced by slash treatment. In addition to attenuating rainfall-erosivity, slash aids in reducing the rate at which rainfall reaches the soil surface through interception, thus increasing infiltration. Furthermore, slash scattered on a slope decreases the length of slope able to generate an increased depth of runoff; where runoff depth can be proportional to erosion (Dunne and Leopold 1978). These effects further promote infiltration and lead to increased soil moisture. We believe slash treatment changes the microclimate of the soils and increases the ability of herbaceous species to germinate.

Almost 4 years after the slash treatment was imposed on the watershed, studies and observations have provided significant evidence to the successful re-establishment of herbaceous ground cover in intercanopy areas. Jacobs et al. (2000) found a 7-fold increase in herbaceous cover in the treatment watershed within the second year of post-treatment. Vegetation cover measurements, at 4 different times during our study (pre and post growing seasons 2000 and 2001), found continuing success in forbs and grasses in the treatment microwatersheds while the control microwatersheds appear to remain unchanged or continue to degrade (Figure 5).

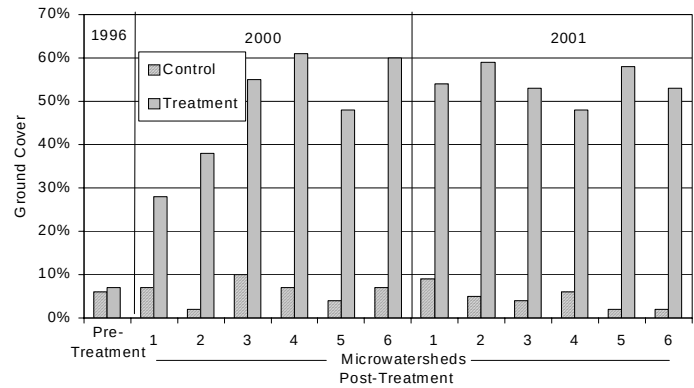


Figure 5. 1996 Pre-treatment ground cover in the 35-hectare control watershed and the 41-hectare treatment watershed (Gatewood 1999); and average—pre and post growing season 2000–2001—post-treatment ground cover for all 6 control microwatersheds and 6 treatment microwatersheds.

Wood et al. (1987) examined multiple variables influencing sediment production in New Mexico watersheds and determined total ground cover to be the single most important variable. Based on the regression analyses there is an exponential increase in sediment yield on non-pumice soils associated with a decrease in intercanopy ground cover (including slash and litter), regardless of pre or post growing season. A similar relationship exists with pumice soils, but the analysis is limited to 4 data points. As suggested by Davenport et al. (1998) a threshold may exist in these degraded piñon-juniper woodlands where intercanopy ground cover less than 15–20% results in high magnitude sediment yield (Figure 6). Our data show that the slash treatment increases total ground cover beyond this erosion threshold, resulting in markedly lower erosion rates.

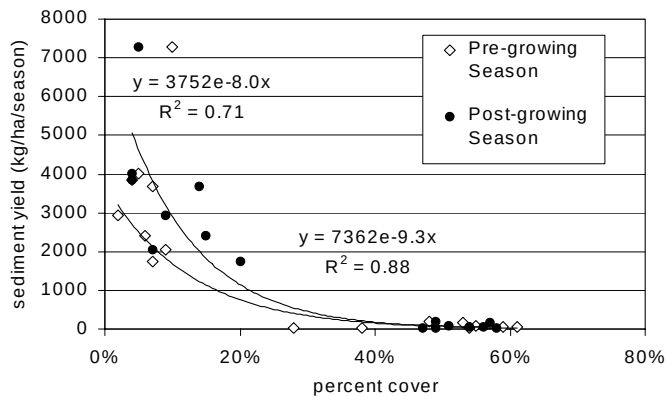


Figure 6. Relationship of intercanopy ground cover and sediment yield for non-pumice soils.

Average ground cover: pre-growing season (June 2000-2001), $n = 16$; post-growing season (September 2000-2001), $n = 16$, 2000 and 2001.

CONCLUSIONS

Intercanopy areas of degraded piñon-juniper woodlands of Bandelier National Monument are experiencing accelerated erosion. A lack of ground cover facilitates the processes of rainsplash erosion, rilling, and channelization. Subsequently, these processes increase interconnectivity of intercanopy areas and promote the rapid export of soil and nutrients from larger areas. If these processes are allowed to continue or intensify, these degraded piñon-juniper woodlands may not be able to sustain a productive ecosystem. Wholesale loss of the cultural resources embedded in the soil profile will be inevitable as well.

In a 2-season study, conducted during the months of June-September, we consistently measured 2-orders of magnitude less sediment yield using slash-treated microwatersheds when compared to untreated microwatersheds in degraded piñon-juniper woodlands. Watershed restoration studies in Bandelier National Monument are providing evidence that ground protection, with the thinning of young, dense piñon and juniper trees and scattering of branches and stems in intercanopy areas, greatly reduces

accelerated sediment yield. We believe that the scattering of branches and stems from thinned piñon and juniper trees acts to attenuate rainfall-erosivity and increase infiltration and soil moisture, thus promoting natural regeneration of an herbaceous cover within the intercanopy areas. This increase in ground cover is shown to markedly reduce erosion rates and potentially bring the system across a suggested sustainable threshold.

Additionally, we measured statistically significant sediment yield difference between slash treated and untreated microwatersheds on two different soil types, non-pumice and pumice soils. Microwatersheds with non-pumice soils experienced 2-100 times more sediment yield than microwatersheds with pumice soils. Davenport (1997) indicates non-pumice soils comprise a major proportion of the paired watersheds and are most susceptible to erosion hazards.

Results from our study, and on going archeological, wildlife, and soil surveys will aid in the identification of high priority areas of Bandelier National Monument in need of restoration. As a result of a temporarily increased fire hazard associated with slash treatment, we would suggest implementing a patch-like mosaic of slash treatment across high priority degraded piñon-juniper woodlands. A patch-like mosaic will reduce a continuum of fuels over large areas and minimize the threat of catastrophic fire. Restored piñon-juniper woodlands—as the result of slash treatment—provides a productive ecosystem with natural sediment yields/soil loss rates and a forest structure similar to pre-grazing and pre-fire suppression conditions which decrease catastrophic fire hazards.

REFERENCES

- Allen, C.D. 2001. Runoff, Erosion, and Restoration Studies in Piñon-Juniper Woodlands of the Pajarito Plateau. Pp. 24-26 In: P.S. Johnson (ed.). Water, Watersheds, and Land Use in New Mexico. New Mexico Decision-Makers Field Guide No. 1. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.
- Allen, C.D. 1989. Changes in the Landscapes of the Jemez Mountains. Ph.D. dissertation, Univ. of California, Berkeley, CA.
- Allen, C.D. and D.D. Breshears. 1998. Drought induced shift of a forest/woodland ecotone: Rapid landscape response to climate variation. *Proceedings of the National Academy of Sciences (USA)* 95: 14839-14842.
- Bandelier National Monument. 2001. Archived climate and precipitation data for Bandelier National Monument, New Mexico from 1925-2001. On file Bandelier National Monument.
- Bowen, B.M. 1996. Rainfall and climate variation over a sloping New Mexico plateau during the North American Monsoon. *Journal of Climate* 9: 3432-3442.
- Brown, L.C., and G.R. Foster. 1987. Storm erosivity using idealized intensity distributions. In Renard, K.G. et al. Predicting soil erosion by water: A guide to conservations planning with the revised universal sediment yield equation (RUSLE). USDA, Agriculture Handbook No. 703, 404 pp.
- Gatewood, R. 1999. Ecological Response to Tree Thinning within Degraded Piñon-Juniper Woodland in Bandelier National Monument; 3-year post treatment report. On file Bandelier National Monument, 18 p.
- Gottfried, G.J., T.W. Swetman, C.D. Allen, J.L. Betancourt, and A. Chung-MacCoutbrey. 1995. Piñon-Juniper Woodlands of the Middle Rio Grande Basin, New Mexico. pp. 95-132 In: D.M. Finch and J.A. Tainter (tech. eds.). Ecology, Diversity, and Sustainability of the Middle Rio Grande Basin. USDA For. Serv. Gen. Tech. Rep. RM-268, Fort Collins, Colorado. 186 p.
- Davenport, D.W., D.D. Breashers, B.P. Wilcox, and C.D. Allen. 1998. Viewpoint: Sustainability of piñon-juniper ecosystems-a unifying perspective of soil erosion thresholds. *J. Range Management* 51: 231-240.
- Davenport, D.W. 1997. Soil Survey of Three Watersheds on South Mesa, Bandelier National Monument, New Mexico. On file Bandelier National Monument, NM.
- Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman and Company. New York. 818 p.
- Earth Environmental Consultants, Inc. 1974. Soil survey and survey of range and ecological conditions on a southern part of Bandelier National Monument. Unpublished report to USDI National Park Service, Southwest Region, Santa Fe, NM. 29p.
- Foster, G.R., F. Lombardi, and W.C. Moldenhauer. 1982. Evaluation of Rainfall-Runoff Erosivity Factors for Individual Storms. *Transactions of the ASAE* 25(1): 124-129.
- Jacobs, B.F., R.G. Gatewood, and C.D. Allen, 2000. Ecological Restoration of a Wilderness and Cultural Landscape: Paired Watershed Study. Bandelier National Monument: Interim Report to U.S. Geological Survey, on file at Bandelier National Monument, 20 p.
- Jacobs, B.F. and R.G. Gatewood. 1999. Restoration Studies in Degraded Piñon-Juniper Woodlands of North-Central New Mexico. In S.B. Monsen and R. Stevens, *Proceedings: ecology and management of piñon-juniper communities within the Interior West*; pp. 294-298. 1997 September 15-18; Provo, UT. Proc. RMRS-P-9. USDA, Forest Service, Rocky Mountain Research Station.

- Javed, Nasim. 1991. Hydrologic Responses to Fuelwood Harvest and Slash Disposal on a Piñon-Juniper Dominated Grassland Site in the Gila National Forest, New Mexico. PhD Dissertation. New Mexico State University, Las Cruces, New Mexico
- Julius, C. 1999. A comparison of vegetation structure on three different soils at Bandelier National Monument, New Mexico, USA. Unpublished report on file at Bandelier National Monument. 72 p.
- Los Alamos National Laboratory (LANL). 2001. Aerial photography of the Pajarito Plateau, NM.
- Mitchell, J.E. and T.C. Roberts Jr. 1999. Distribution of Piñon-Juniper in the Western United States. *In* S.B. Monsen and R. Stevens, Proceedings: ecology and management of piñon-juniper communities within the Interior West; pp. 294-298. 1997 September 15-18; Provo, UT. Proc. RMRS-P-9. USDA, Forest Service, Rocky Mountain Research Station.
- Reid, K.D., B.P. Wilcox, D.D. Breshears, and L.H. MacDonald. 1999. Runoff and erosion in a piñon-juniper woodland: Influence of Vegetation Patches. *Soil Science Society of America Journal* 63:1869-1879.
- Renard, K. G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). *Agricultural Handbook Number 703*, 404 p. Agricultural Research Service, Tucson, AZ.
- Reneau, S.L. & E.V. McDonald, 1996. Landscape History and Processes on the Pajarito Plateau, Northern New Mexico. Rocky Mountain Cell, Friends of the Pleistocene Field Trip Guidebook, September 12-15, 1996. Los Alamos, New Mexico.
- Sydoriak, C.A., C.D. Allen, and B.F. Jacobs. 2000. Would ecological landscape restoration make the Bandelier Wilderness more or less of a wilderness? pp. 209-215 *In*: D.N. Cole, S.F. McCool, W.T. Borrie, and F. O'Loughlin (comps.). *Proceedings: Wilderness Science in a Time of Change Conference-Volume 5: Wilderness Ecosystems, Threats, and Management*; 1999 May 23-27; Missoula, MT. USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-15-VOL-5. Ogden, UT.
- Ulsaker, L.G. and C.A. Onstad. 1984. Relating Rainfall Erosivity Factors to Sediment yield in Kenya. *Soil Science Society of America* 48: 891-896.
- Wischmeier, W.H., & D.D. Smith. 1958. Rainfall Energy and Its Relationship to Sediment yield. *Transactions, American Geophysical Union* 39:285-291.
- Wilcox, B.P. 1994. Runoff and erosion in intercanopy zones of a piñon-juniper woodlands, New Mexico. *Journal of Range Management* 47:285-295.
- Wilcox, B.P., B.D. Newman, C.D. Allen, K.D. Reid, D. Brandes, J. Pitlick, and D.W. Davenport. 1996a. Runoff and erosion on the Pajarito Plateau: Observations from the field. p. 433-439. *In* F. Goff et al. (ed.) *New Mexico geological society uidebook*. NMGS, Socorro, NM.
- Wilcox, B.P., J. Pitlick, C.D. Allen, and D.W. Davenport, 1996b. Runoff and erosion from a rapidly eroding piñon-juniper hillslope. p. 61-77. *In* M.G. Anderson and S.M. Brooks (ed.) *Advances in hillslope processes*. John Wiley & Sons, New York.
- Wilcox, B.P., D.D. Breshears, and C.D. Allen. 2003. *Ecohydrology of a resource-conserving semiarid woodland: Temporal and spatial scaling and disturbance*. *Ecological Monographs* (in press).
- Wood, J.C., M.K. Wood, and J.M. Tromble. 1987. Important factors influencing water infiltration and sediment production on arid lands in New Mexico. *Journal of Range Management* 12:111-118.