

Rapidly Eroding Piñon–Juniper Woodlands in New Mexico: Response to Slash Treatment

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ABSTRACT

The piñon (*Pinus edulis* Engelm.)–juniper [*Juniperus monosperma* (Engelm.) Sarg.] woodlands of Bandelier National Monument are experiencing accelerated erosion. Earlier studies suggest that causes of these rapidly eroding woodlands are related to an unprecedented rapid transition of ponderosa pine (*Pinus ponderosa* C. Lawson) savanna to piñon–juniper woodlands as a result of cumulative historical effects of overgrazing, fire suppression, and severe drought. To study the effectiveness of slash treatment in reducing accelerated erosion, we used sediment check dams to quantify sediment yield from twelve paired microwatersheds (300–1100 m²) within an existing paired watershed study. Six of the twelve microwatersheds were located in a 41-ha (treatment) watershed with scattered slash treatment, whereas six 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). In response to slash treatment, mean seasonal sediment yield for 2000 equaled 2.99 Mg/ha in the control vs. 0.03 Mg/ha in the treatment and 2.07 Mg/ha in the control vs. 0.07 Mg/ha in the treatment in 2001. The practice of slash treatment demonstrates efficacy in reducing erosion in degraded piñon–juniper woodlands by encouraging herbaceous recovery. Our data show that 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 decrease catastrophic fire hazard.

IN THE SOUTHWESTERN UNITED STATES, piñon–juniper 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 ha (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 U.S. National Park Service 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 cumulative, historical

effects of overgrazing, fire suppression, and a severe drought in the 1950s (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 the fact 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 above mean sea level), these former communities included well-developed soils and herbaceous understories that protected the soil from rapid erosion and provided a largely continuous fuel matrix that 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 1880s, and were not eliminated from Bandelier National Monument until 1932. However, feral burros continued to cause widespread effects on the herbaceous understory and soil effects 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 1900s (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 1950s 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 effects provided the opportunity for fire-sensitive, more drought-resistant piñon and juniper to become established in densities unprecedented for at least the past 800 yr (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).

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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 1040 cultural artifacts moved by a single rainfall-runoff event into a sediment trap draining only 1 ha 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 more than 2500 surveyed archeological sites scattered over 13 629 ha 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 yr, 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 initiated the Bandelier Watershed Restoration Project to validate positive results of previous small-scale plot studies using slash treatment (the mechanical thinning of piñon-juniper and subsequent scattering of stems and branches over intercanopy areas).

Multiple runoff and erosion studies have been conducted across piñon-juniper woodlands on the Pajarito Plateau of north-central New Mexico (Wilcox et al., 2003, 1996a,b; Allen, 2001; Davenport et al., 1998; Reid et al., 1999; Wilcox, 1994). After 9 yr 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 Mg/ha/yr (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 3.30 Mg/ha (CV = 69%) compared with canopy areas, which experienced sediment yield rates of 0.06 Mg/ha (no replicates). Additional local studies conducted by Reid et al. (1999) and Wilcox et al. (2003) 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.

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.

MATERIALS AND 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) (Fig. 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 to 100 m in thickness. These volcanics were erupted from the Jemez Mountains approximately 1.22 million years ago 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 before the eruption and deposition of the pumice about 60 000 yr before present (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 and 1980 m. This elevation approaches the highest elevation limit (approximately 2300 m) for piñon-juniper woodlands in 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°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

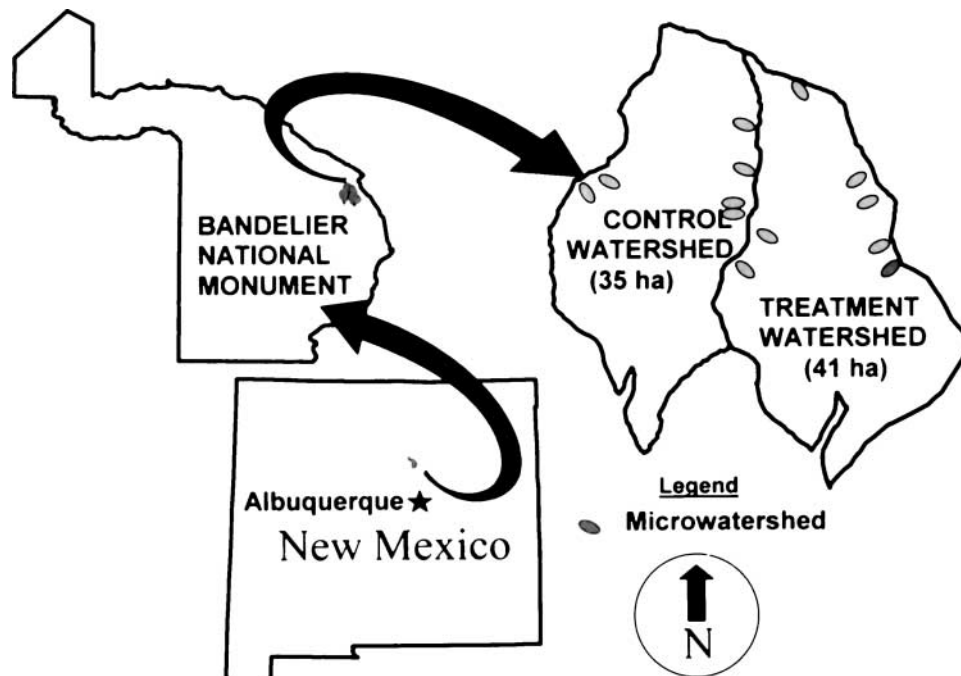


Fig. 1. Study location: Bandelier Watershed Restoration Project, Bandelier National Monument, New Mexico.

rains associated with this period are characterized by localized, high-intensity, short-duration rainfall. Total precipitation during these three months is generally 40 to 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 with an untreated (control) watershed. The watersheds are adjacent and similar in size (treatment = 41 ha, control = 35 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 pre-treatment 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 six microwatersheds (300–1100 m²) within each watershed. The small microwatersheds were delineated and surveyed with a Nikon (Tokyo, Japan) 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: (i) aspect, (ii) slope position = upper one-third slope, (iii) slope, and (iv) soil type. Four replicates located on the west aspect of each watershed represent nonpumice 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 nonpumice). 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 three 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 (Los Alamos National Laboratory, 2001) 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 gauge with 0.25-mm resolution (12 total rain gauges). Precipitation data (total storm precipitation, duration, and intensity) were collected using HOBO data loggers (Onset Computer Corp., Bourne, MA) with 1-min 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 min. Precipita-

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

The highest 30-min intensity (I_{30}) in mm/h was obtained by using data output from HOBO data loggers for 1-min intensity data for each sediment yield-producing storm. Storm rainfall energy was calculated empirically using the 30-min intensity data and the 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-min highest intensity (mm/h).

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-min 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 storm rainfall erosivity (EI_{30}), in newtons per hour (N/h), for each sediment yield-producing storm using the above energy equation and the highest 30-min rainfall intensity determined from 1-min resolution data for each rain gauge.

Sediment Yield Measurements

Sediment check dams were constructed at the outlet of each microwatershed. The check dams measured between 1.8 to 3.7 m in length and up to 0.6 m in height and were constructed of welded wire mesh, covered with permeable geotextile (silt fence), and secured into the ground with rebar. Check dam basin volumes ranged 0.18 to 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 two seasons (2000 and 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 kg 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 ha (1 m²) from total station surveys data and Surfer software (RockWare, 2000). Mass of sediment per unit area (Mg/ha) was calculated for each microwatershed per rainfall-runoff event.

RESULTS AND DISCUSSION

Storm Analysis

The total precipitation for the two, 4-mo periods was below average for both years when compared with long-

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

Characteristic	Microwatershed						Treatment					
	1	2	3	4	5	6	1	2	3	4	5	6
Area, ha	0.086	0.055	0.032	0.071	0.078	0.034	0.072	0.097	0.063	0.076	0.103	0.132
Hillslope length, m	73	72	45	43	45.5	53	60.5	50.5	54	69	45	52
Slope, %	0.13	0.13	0.14	0.16	0.17	0.13	0.10	0.13	0.13	0.13	0.22	0.15
Canopy cover, %	0.55	0.33	0.49	0.57	0.49	0.63	0.11	0.26	0.12	0.28	0.20	0.21
Ground cover [†] , %	0.14/0.08	0.06/0.05	0.08/0.04	0.11/0.11	0.07/0.04	0.11/0.02	0.39/0.51	0.48/0.57	0.53/0.55	0.59/0.49	0.48/0.56	0.54/0.49
Soil type [‡]	Inceptisol (nonpunice)	Inceptisol (nonpunice)	Alfisol (nonpunice)	Alfisol (nonpunice)	Andisol (punice)	Andisol (punice)	Inceptisol (nonpunice)	Alfisol (nonpunice)	Alfisol (nonpunice)	Alfisol (nonpunice)	Andisol (punice)	Andisol (punice)
Soil bulk density, Mg/m ³	1.26	1.21	1.43	1.30	0.60	0.96	1.14	1.40	1.30	1.29	0.78	0.77

[†] Average pre- and post-growing seasons (June 2000 and 2001/September 2000 and 2001).

[‡] As described by Davenport (1997) and Julius (1999).

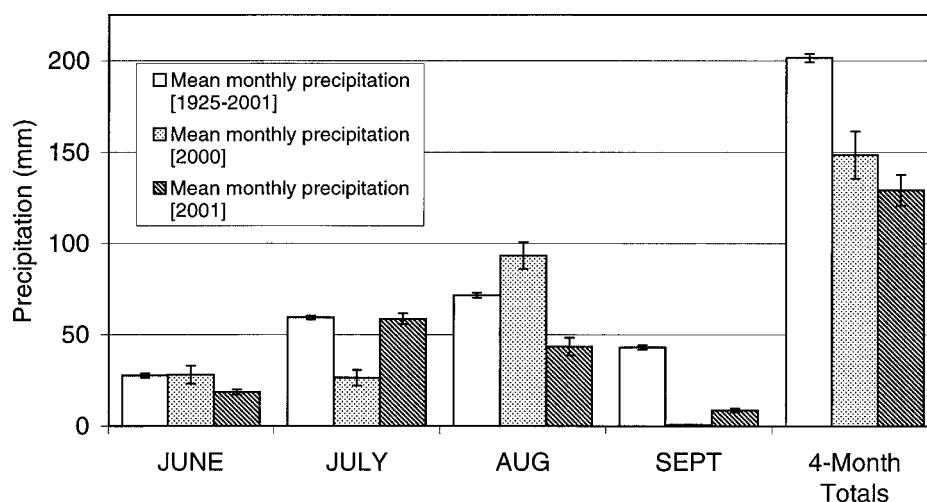


Fig. 2. Study-period precipitation (2000–2001) versus long-term average precipitation (1925–2001). Historical precipitation error bars represent one standard deviation with 76 yr of data. Error bars for 2000–2001 data represent one standard deviation of 12 rain gauges. June 2000 represents mean precipitation and standard deviation of three rain gauges.

term averages (Fig. 2). A total of 41 precipitation events (>1 mm), including one 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 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 min. These short-duration, high-intensity storms are associated with high rainfall erosivity, a significant component for sediment yield.

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 (Fig. 3). In 2000, the six control microwatersheds exhibited a mean sediment yield of 2.99 Mg/ha/season, whereas the six treated microwatersheds exhibited a mean sediment yield of only 0.03 Mg/ha/season. In 2001, the six control microwatersheds exhibited a mean sediment yield of 2.07 Mg/ha/season, whereas six treated microwatersheds exhibited a mean sediment yield of 0.07 Mg/ha/season. Table 3 lists sediment yields for both the control and treated microwatersheds in 2000 and 2001.

Over the two-season study, most of the total sediment yield resulted from one or two large convective thunderstorms each season. On 9 Aug. 2000, we recorded a mean of 16.8 mm of rain in less than 1 h with a peak rainfall intensity of 167.6 mm/h (calculated from 1-min data) and mean rainfall erosivity of 25.5 N/h. The storm

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

Storm date	Storm type	Mean total† storm precipitation	Highest‡ 1-min intensity	Highest‡ 30-min intensity (<i>I</i> ₃₀)	Highest‡ rainfall erosivity (<i>EI</i> ₃₀)
		mm	mm/h		N/h
2000					
28 June	convective	6.1 (17%)§	106.7	18.3	9.5 (23%)
17 July	convective	2.9 (23%)	53.3	14.5	7.3 (73%)
25 July	convective	7.0 (20%)	15.2	8.1	5.7 (38%)
29 July	convective	8.4 (11%)§	61.0	19.6	10.6 (10%)
6 August	convective	5.3 (22%)¶	91.4	14.7	7.2 (33%)
9 August	convective	16.8 (12%)	167.6	38.6	25.5 (22%)
15 August	convective	5.5 (17%)	76.2	12.7	5.8 (23%)
18 August	frontal	65 (7%)	91.4	16.3	8.2 (18%)
2001					
19 June	convective	10.4 (4%)	30.5	15.2	7.5 (9%)
2 July	convective	30.5 (8%)	167.6	60.2	42.7 (12%)
14 July	convective	4.9 (17%)	61.0	12.2	5.4 (23%)
1 August	convective	6.6 (8%)	15.2	9.1	3.7 (15%)
10 August	convective	8.7 (21%)	61.0	21.8	12.1 (32%)
12 August	convective	9.5 (13%)	30.5	16.3	8.2 (22%)
16 September	convective	6.7 (8%)§	61.0	14.7	7.1 (12%)

† Mean precipitation totals of 12 rain gauges (coefficient of variation).

‡ Highest value recorded and/or calculated from any 1 of 12 rain gauges.

§ Mean and coefficient of variation for 11 rain gauges.

¶ Mean and coefficient of variation for 10 rain gauges.

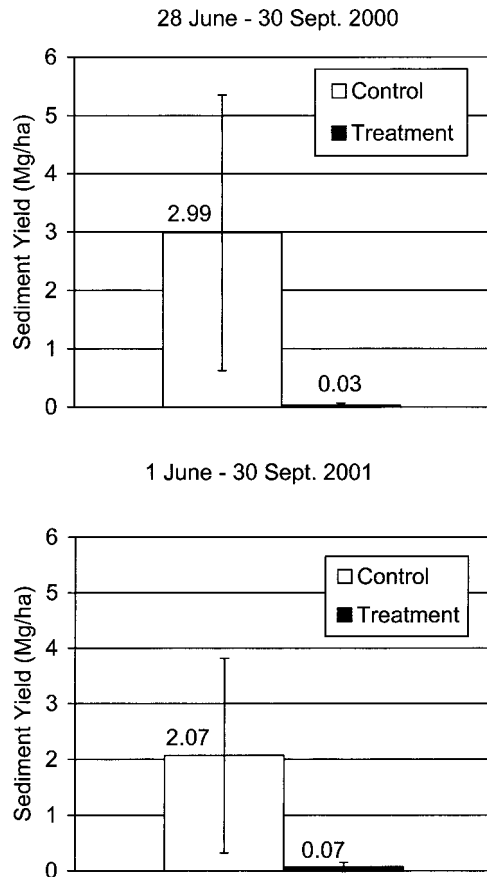


Fig. 3. Seasonal sediment yields (Mg/ha) for treatment ($n = 6$) and control ($n = 6$) microwatersheds, 2000 and 2001. Error bars represent one standard deviation.

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 2 July 2001, we recorded a mean of 26 mm of rain in less than 30 min with a peak rainfall intensity of 167.6 mm/h and mean rainfall erosivity of 42.7 N/h. The 2 July 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 and 2001 have a recurrence interval equal to or less than 2 yr while the 2 July 2001 storm may have a less frequent return period of between 2 and 10 yr when compared with a 10-yr 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 18–19 Aug. 2000 recorded more than three times the rainfall depth as the 9 Aug. 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 six control microwatersheds ($n = 90$, $r^2 = 0.48$) and the six 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 with other single variables: amount of precipitation, rainfall energy, and rainfall intensity. Our data suggest slash treatment aids in reducing the effect of rainfall erosivity on sediment yield (Fig. 4). Variability associated with regressing rainfall erosivity and sediment yield was partially contributed by soil type (pumice vs. nonpumice 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 one to three 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, nonpumice microwatersheds exhibited sediment yields one to two orders of magnitude more than pumice microwatersheds, irrespective of treatment effects (with the exception of C5 in 2000). In 2001, nonpumice microwatersheds experienced sediment yields two orders of magnitude greater than for pumice microwatersheds across treatment and control area. Table 3 illustrates

Table 3. Total seasonal sediment yields in 2000 and 2001 for individual control (C) and treatment (T) microwatersheds.

Microwatershed	Area ha	Soil description	Sediment yield	
			2000	2001
			— Mg/ha —	
C1	0.09	nonpumice	1.74	2.30
C2	0.06	nonpumice	2.95	4.07
C3	0.03	nonpumice	7.28	4.01
C4	0.07	nonpumice	3.67	2.41
C5	0.08	pumice	1.76	0.08
C6	0.03	pumice	0.54	0.04
T1	0.07	nonpumice	0.02	0.04
T2	0.10	nonpumice	0.02	0.05
T3	0.06	nonpumice	0.10	0.17
T4	0.08	nonpumice	0.05	0.20
T5	0.10	pumice	0.001	0.01
T6	0.13	pumice	0.003	0.004

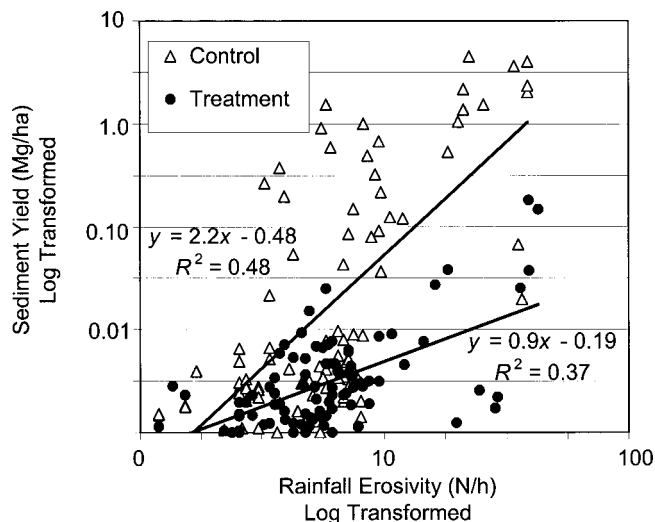


Fig. 4. Effects of slash treatment on soil loss as a function of rainfall erosivity, 2000 and 2001. Control, $n = 90$; treatment, $n = 90$. Data are transformed using the natural logarithm.

sediment yields for each microwatershed for each season. Based on our data, we suggest the nonpumice soils (Inceptisols, Alfisols) have a high soil erosion hazard relative to pumice soils (Andisols). In fact, nonpumice soils in untreated (control) microwatersheds consistently exhibited seasonal sediment yields exceeding local soil survey annual tolerance levels of 2.20 Mg/ha (Earth Environmental Consultants, unpublished data, 1974).

We suggest the reason for the significant differences in sediment yield between the nonpumice 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 nonpumice 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 two-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 nonpumice 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 yr after the slash treatment was imposed on the watershed, studies and observations have provided significant evidence to the successful reestablishment of herbaceous ground cover in intercanopy areas. Jacobs et al. (2000) found a sevenfold increase in herbaceous cover in the treatment watershed within the second year of post-treatment. Vegetation cover measurements, at four 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 (Fig. 5).

Wood et al. (1987) examined multiple variables influencing sediment production in New Mexico watersheds

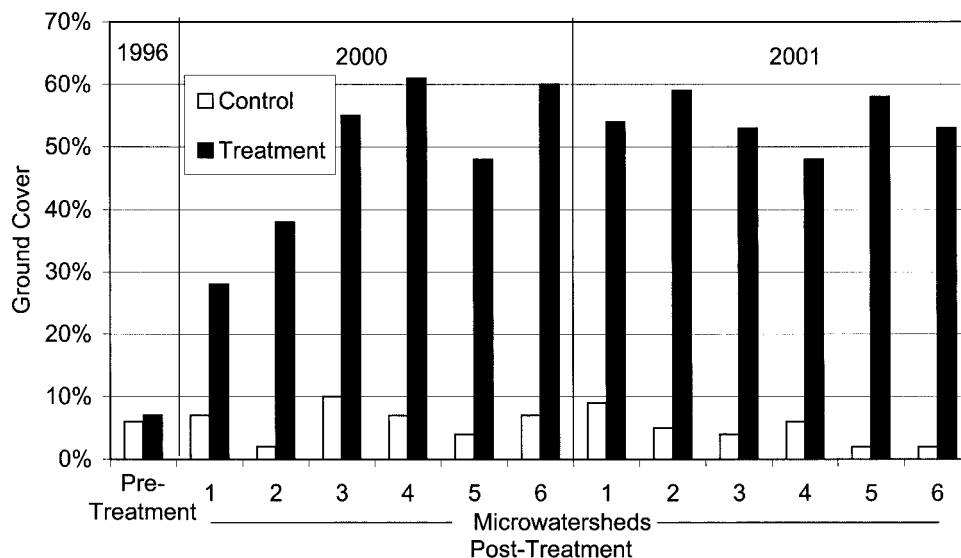


Fig. 5. Pre-slash treatment (1996) ground cover within the control and treatment watersheds as compared to post-slash treatment ground cover for each microwatershed during the study period (2000 and 2001). Ground cover includes slash and vegetation in intercanopy areas.

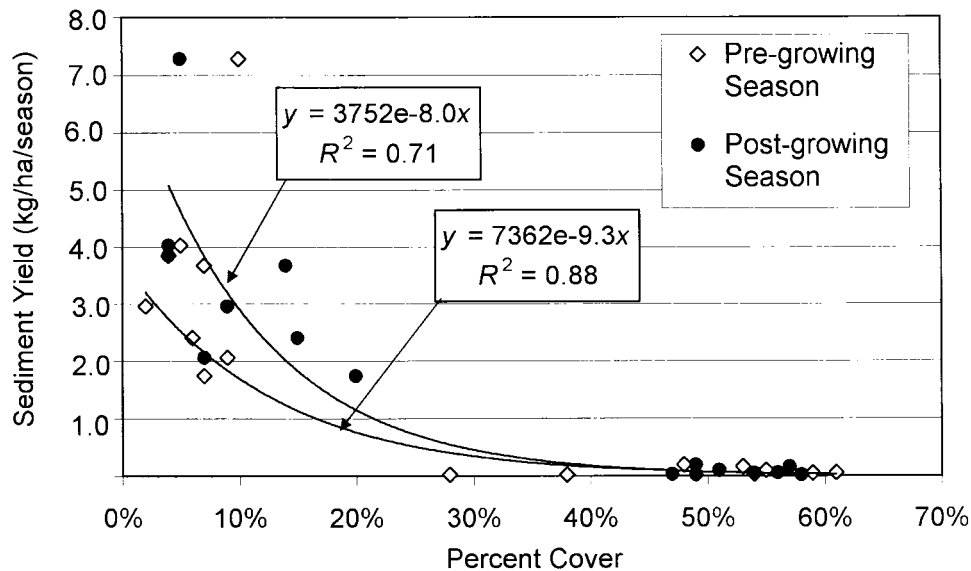


Fig. 6. Relationship of intercanopy ground cover and sediment yield for nonpumice soils. Average ground cover: pre-growing season (June 2000 and 2001), $n = 16$; post-growing season (September 2000 and 2001), $n = 16$.

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 nonpumice 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 four 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 to 20% results in high-magnitude sediment yield (Fig. 6). Our data show that slash treatment increases total ground cover beyond this erosion threshold, resulting in markedly lower erosion rates.

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 two-season study, conducted during the months of June–September, we consistently measured two orders of magnitude less sediment yield using slash-treated microwatersheds when compared with 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, nonpumice and pumice soils. Microwatersheds with nonpumice soils experienced 2 to 100 times more sediment yield than microwatersheds with pumice soils. Davenport (1997) indicates nonpumice soils comprise a major proportion of the paired watersheds and are most susceptible to erosion hazards.

Results from our study, and ongoing 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, provide a productive ecosystem with natural sediment yields–soil loss rates and a forest structure similar to pre-grazing and pre-fire suppression conditions that decrease catastrophic fire hazards.

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