Rangeland Ecol Manage 60:285–292 | May 2007

#583

Runoff and Erosion After Cutting Western Juniper

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Abstract

Western juniper (*Juniperus occidentalis* spp. *occidentalis* Hook.) has encroached on and now dominates millions of acres of sagebrush/bunchgrass rangeland in the Great Basin and interior Pacific Northwest. On many sites western juniper has significantly increased exposure of the soil surface by reducing density of understory species and surface litter. We used rainfall and rill simulation techniques to evaluate infiltration, runoff, and erosion on cut and uncut field treatments 10 years after juniper removal. Juniper-dominated hillslopes had significantly lower surface soil cover of herbaceous plants and litter and produced rapid runoff from low-intensity rainfall events of the type that would be expected to occur every 2 years. Direct exposure of the soil to rainfall impacts resulted in high levels of sheet erosion ($295 \text{ kg} \cdot \text{ha}^{-1}$) in juniper-dominated plots. Large interconnected patches of bare ground concentrated runoff into rills with much higher flow velocity and erosive force resulting in rill erosion rates that were over 15 times higher on juniper-dominated plots. Cutting juniper stimulated herbaceous plant recovery, improved infiltration capacity, and protected the soil surface from even large thunderstorms. Juniper-free plots could only be induced to produce runoff from high-intensity events that would be expected to occur once every 50 years. Runoff events from these higher-intensity simulations produced negligible levels of both sheet and rill erosion. While specific inferences drawn from the current study are limited to juniper-affected sites in the Intermountain sagebrush steppe, the scope of ecosystem impacts are consistent with woody-plant invasion in other ecosystems around the world.

Resumen

El "Western juniper" (*Juniperus occidentalis* spp. *occidentalis* Hook.) se ha expandido, y ahora domina millones de hectáreas de pastizal de "Sagebrush/Bunchgrass" en la Gran Cuenca y en la región interior del Pacifico Noroeste. En muchos sitio el "Western juniper" ha aumentado significativamente la exposición del suelo al reducir la densidad de las especies herbáceas y del mantillo superficial. Utilizamos técnicas de simulación de lluvia y canalillos para evaluar la infiltración, el escurrimiento y la erosión en tratamientos de campo con corte y sin corte 10 años después de remover el "Western juniper". Las laderas de las colinas dominadas por "Western juniper" tenían significativamente menos cobertura de plantas herbáceas y mantillo y produjeron un escurrimiento rápido a partir de eventos de lluvia de baja intensidad, del tipo que se esperaría ocurrieran cada dos años. En las parcelas dominadas "Western juniper", la exposición directa del suelo a los impactos de la lluvia resultó en altos niveles de erosión laminar ($295 \text{ kg} \cdot \text{ha}^{-1}$). Grandes parches de suelo desnudo interconectados concentraron el escurrimiento en los canalillos con una mayor velocidad de flujo y fuerza erosiva, resultando en tasas de erosión de surco 15 veces mayor que en las parcelas dominadas por "Western juniper". La remoción del "Western juniper" estimulo la recuperación del estrato herbáceo, mejoró la capacidad de infiltración y protegió la superficie del suelo, aun de las grandes tormentas. Las parcelas libres de "Western juniper" pudieran ser inducidas a producir escurrimiento solo a partir de eventos de lluvia de alta intensidad, que se esperaría ocurrieran una vez cada 50 años. Los eventos de escurrimiento de la simulación de lluvias de alta intensidad produjeron niveles insignificantes de erosión laminar y de surco. Mientras que las inferencias específicas derivadas de nuestro estudio esta limitadas a sitios afectados por "Western juniper" en la estepa intermontañosa montañosa de "Sagebrush" el alcance de los impactos en el ecosistema son consistentes con la invasión de especies leñosas en otros ecosistemas alrededor del mundo.

Key Words: hydrology, infiltration, overland-flow, sagebrush

INTRODUCTION

Semiarid ecosystems throughout the world are experiencing changes in vegetation structure and ecosystem function due to management activities, altered fire regimes, increased levels of atmospheric CO_2, and global climate change (Archer 1995; LeMaitre et al. 1996; Brown and Archer 1999; Gill and Burke 1999; Miller and Rose 1999; Bond and Midgley 2000; Miller et al. 2000; Van Auken 2000; Hastings et al. 2003; Polley et al. 2003; Huxman et al. 2005). Western juniper (*Juniperus occidentalis* spp. *occidentalis* Hook.) is encroaching into sagebrush/bunchgrass communities throughout the intermountain West and now dominates millions of acres of rangeland in Oregon, Idaho, Nevada, and California (Miller et al. 2005). Western juniper dominance has been shown to decrease shrub and herbaceous cover, particularly on soils that contain a shallow root-restricting layer (Burkhardt and Tisdale 1969; Miller et al. 2000). Vegetation responses to juniper control related to recovery of grass and shrub species have been

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Manuscript received 16 November 2005; manuscript accepted 15 January 2007.

Table 1. Mean (± SE) canopy cover (%) and litter cover (%), rock cover (%), and bare ground (%) in areas with no canopy cover for juniper woodland and juniper removed plots 1991, 1993, and 1997.[1] Cover values for 1991 are prior to application of juniper control treatment. Lowercase letters denote significant treatment differences for canopy cover by year.

	1991		1993		1997	
	Juniper woodland	Juniper removed	Juniper woodland	Juniper removed	Juniper woodland	Juniper removed
Perennial grass	4.8 ± 0.2	5.2 ± 0.2	3.2 ± 0.4a	16.9 ± 1.3b	3.1 ± 0.3a	16.1 ± 1.5b
Annual grass	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.3	0.2 ± 0.4	0.2 ± 0.3a	4.4 ± 0.6b
Perennial forb	0.2 ± 0.1	0.1 ± 0.1	0.5 ± 0.4a	2.1 ± 0.5b	1.1 ± 0.2	2.5 ± 0.5
Annual forb	0.3 ± 0.1	0.2 ± 0.2	1.8 ± 0.5a	3.7 ± 0.9b	1.1 ± 0.4	1.5 ± 0.5
Total herbaceous	5.3 ± 0.2	5.6 ± 0.1	5.6 ± 0.7a	22.8 ± 1.7b	5.5 ± 0.3a	24.5 ± 1.5b
Litter	2.1 ± 0.5	2.5 ± 0.2	3.2 ± 0.6a	7.1 ± 1.6b	2.5 ± 0.5a	17.6 ± 4.5b
Rock	9.1 ± 1.2	8.7 ± 1.1	8.7 ± 0.3	9.4 ± 0.3	9.6 ± 0.3	7.9 ± 0.6
Bare	84.0 ± 2.3	85.0 ± 4.7	83.0 ± 3.3a	65.0 ± 3.2b	82.4 ± 2.7a	50.0 ± 3.7b

[1] Data reproduced from Bates et al. (1998).

relatively well documented in this region (Burkhardt and Tisdale 1969; Bates and Miller 1998; Bates et al. 2000; Miller et al. 2000; Bates et al. 2005). Less information is available on the specific impacts of western juniper on infiltration, runoff, and erosion. Research from pinyon-juniper watersheds in the Southwest, however, consistently demonstrates a strong relationship between vegetation cover and soil erosion by wind and water (Wilcox 1994; Baker et al. 1995; Reid et al. 1999; Hastings et al. 2003). Runoff and erosion rates in pinyon-juniper are highest in bare-interspace areas and lowest near tree bases that are protected by the canopy and relatively high levels of ground cover (Wilcox et al. 1996; Reid et al. 1999). Management practices that maintain adequate ground cover on pinyon-juniper hillslopes reduce soil loss and improve site productivity (Baker et al. 1995; Hastings et al. 2003).

The purpose of this study was to quantify hydrologic changes associated with vegetation recovery after western juniper control on a sagebrush-bunchgrass range site in eastern Oregon. Specific objectives were to measure changes in surface runoff, interrill erosion, and rill erosion as a function of rainfall intensity on field sites that had been treated by removal of the juniper canopy 10 years previously (Bates et al. 2000, 2005) and to assess surface soil and vegetation factors that are influencing hillslope hydrology and erosion.

MATERIALS AND METHODS

Study Site

The study was conducted on Steens Mountain in southeast Oregon (lat 118°36′E, long 42°55′N). Elevation at the study site was 1 575 m. Aspect was west facing with 18%–22% slope. The site was dominated by western juniper trees that had established 90 years previously. Juniper fully occupied the site as indicated by limited lateral and terminal leader growth, evident crown lift, and lack of further juniper recruitment (Miller et al. 2000). Juniper canopy cover averaged 27.5%, and tree density averaged 297 trees $\cdot$ ha^{-1} prior to the cutting prescription. Shrubs had been eliminated from the site by juniper competition, although previous shrub occupation was evident from shrub skeletons scattered through the woodland. The dominant shrub prior to juniper encroachment was basin big sagebrush (*Artemisia tridentata* Nutt. spp. *tridentata*). Herbaceous canopy cover averaged 5.5%. Bare ground and rock in the intercanopy zone approached 95% (Bates et al. 2000).

Understory composition was a mixture of native grasses and forbs with Sandberg's bluegrass (*Poa sandbergii* Vasey) the dominant species. Other species characterizing the site were bottlebrush squirreltail (*Sitanion hystrix* [Nutt.] Smith), bluebunch wheatgrass (*Agropyron spicatum* [Pursh] Scribn. & Smith [syn. *Pseudoroegenaria spicata* (Pursh) A. Löve]), Thurber's needlegrass (*Stipa thurberiana* Piper), basalt milkvetch (*Astragalus filipes* Torr.), and pale alyssum (*Alyssum alyssoides* L.). Cheatgrass (*Bromus tectorum* L.) was present across the site (< 1% cover) and was primarily found beneath the juniper canopies (Bates et al. 2000).

Soils were described to the subgroup level from 5 soil pits placed in close proximity to runoff plots. Location of pits was randomly selected. Pits were dug to the restrictive horizon. Four of the soils were described as Typic Vitrixerand with the remaining soil described as a Typic Calcixeroll. The Typic Vitrixerand occurs on most of the site. Soils are underlain by a welded ash tuff of rhyolite/rhyodacite composition, which restricts root penetration of all vegetation at about 50 cm. Climate is cool and moist during winter and spring, while summers are warm and dry. The majority of annual precipitation falls between November and late May. Precipitation (October 1–September 30) at Malheur National Wildlife Refuge weather stations located 27 km southwest (elev. 1 300 m) and 30 km northwest (1 250 m) of the site averages 282 mm and 249 mm.

This site had been sampled since 1991 to assess plant succession in drier-type woodlands following juniper cutting. Table 1 provides an indication of vegetation and ground cover changes on these woodland and cut plots between 1991 and 1997 (Bates et al. 2000).

Experimental Design

This hydrologic study used intact juniper woodlands and juniper woodlands cut in 1991 that had been excluded from grazing since 1997. Treatments consisted of removing juniper by cutting and allowing the understory vegetation to recover for 10 growing seasons and an uncut juniper woodland control. Treatments were randomly stratified across the landscape. Eight 1-ha blocks were established, and the trees within randomly selected halves of each block were cut with chainsaws. Fallen trees were left intact on the site and provided about 20% ground cover. No attempt was made to distribute cut trees or slash across the site. Interspace areas between trees comprised over 70% of the uncut sites, and visual observations indicated that the majority of runoff moved through interspace areas; therefore, study plots were randomly placed in interspaces between trees. Plots in the cut treatment areas were also randomly placed in interspaces between cut trees (Fig. 1).

Rainfall and Overland Flow Simulation

Simulated rainfall was applied to 32.5-m^2 plots using a Colorado State University (CSU) type rainfall simulator (Holland 1969) with 8 stationary sprinklers elevated 3.05 m above the soil surface in June 2001 (Fig. 1). The long axis of each plot was perpendicular to the predominant slope. Plots were installed using sheet-metal flashing pounded into the soil to a depth of approximately 5 cm. The small amount of soil disturbance along the metal was backfilled and compacted. The plot headwalls also extended into the soil surface to a depth of 5 cm (Fig. 1). The upslope edges of the headwalls were sealed using a commercially available cement sealer to stop undercutting and reduce error in soil erosion due to artificial disturbance.

Rainfall was applied simultaneously to a pair of plots for 1 hour at a target rate of 55 $mm \cdot h^{-1}$. To reduce variations between plots within treatments, each plot was prewet with approximately 45 mm of rainfall 16 hours before treatment. Timed grab samples of runoff were collected at 1- or 2-minute time intervals throughout the 60-minute simulation and analyzed for runoff volume and sediment concentration. Total rainfall was determined from the average of 10 plastic depth gages placed on a uniform grid within each plot. Runoff volume and sediment concentration were measured on each runoff sample by weighing the collected runoff sample, then drying the sample at 105°C. The dry sediment samples were then weighed and subtracted from the original sample weight to obtain runoff volume (mm). Total sediment yield ($kg \cdot ha^{-1}$) for each plot was estimated by integrating sediment concentrations and runoff volumes. A sediment-to-runoff ratio ($kg \cdot ha^{-1} \cdot mm^{-1}$) was calculated by dividing total sediment yield by total cumulative runoff volume.

One hour following the rainfall simulation, a flow regulator was used to apply overland flow (rill) rates of 3, 7, 12, and 15 L min^{-1} to each plot. Flow rates were run in consecutive order for 12 minutes each. Runoff samples were collected 4 m downslope of the release point. Measures of runoff volume and sediment concentration were again obtained by oven drying and weighing each sample. Flow velocity in each rill was measured by releasing a concentrated salt solution ($CaCl_2$) into the rill and using electrical conductivity probes at 1- and 3-m intervals downslope to estimate the mean travel time of the salt over a known rill length (Pierson et al. 2003). The conductivity of the water was sampled 8 times each second at each probe while a small ($\sim$ 50 mL) pulse of $CaCl_2$ solution flowed in the rill. The difference in time between the maximum conductivity readings on each probe was recorded as the mean 2-m travel time.

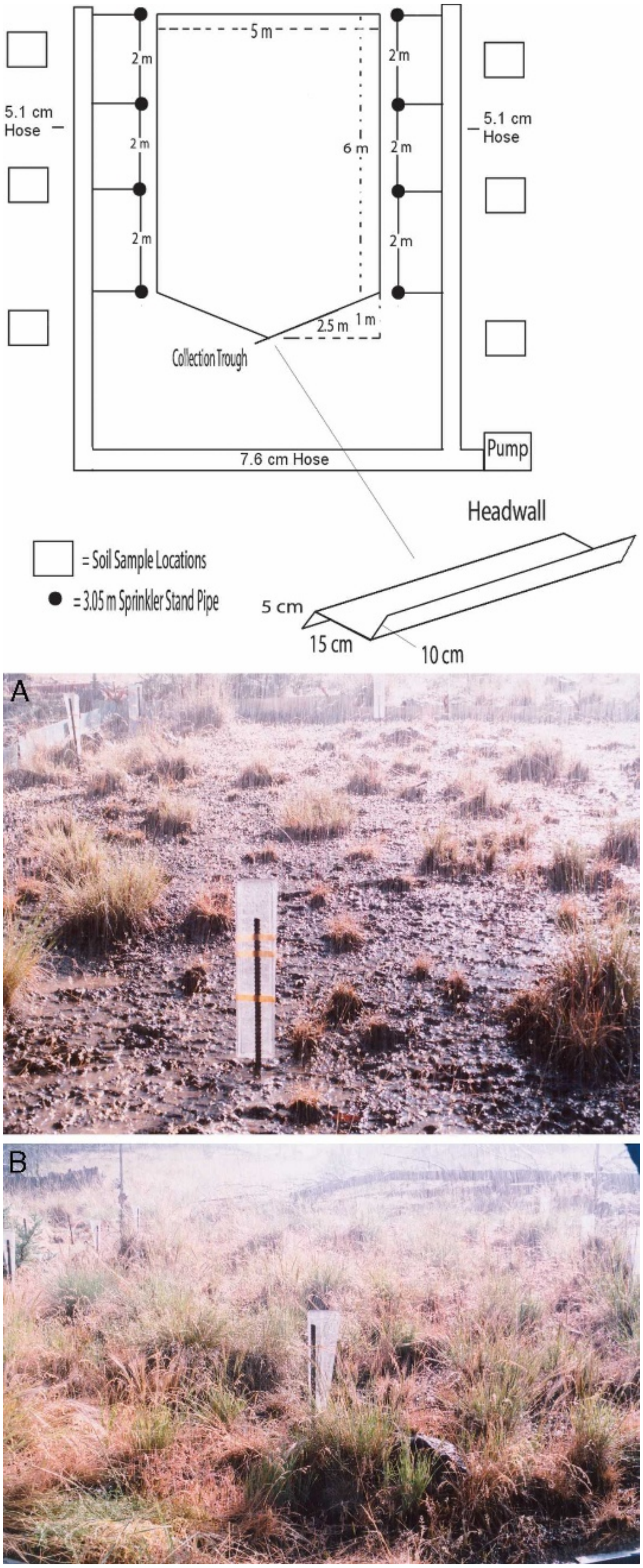

Figure 1. Rainfall simulation plot design and layout. Photos show field plots in juniper woodland (**A**) and juniper removed (**B**) treatments.

Table 2. Mean (± SE) ground cover (%) and canopy cover (%) in the intercanopy zones between trees for juniper woodland and juniper-removed treatments, 2001. Uppercase letters denote significant treatment differences for individual ground cover components between treatments. Lowercase letters denote significant treatment differences for individual canopy cover components.

	Ground cover		Canopy cover	
	Juniper woodland	Juniper removed	Juniper woodland	Juniper removed
Perennial grass	0.2 ± .01A	2.3 ± 0.5B	1.1 ± .05a	12.7 ± 2.6b
Annual grass	0.0 ± 0.0	0.5 ± 0.2	0.02 ± 0.01a	2.9 ± 0.8b
Perennial forb	0.1 ± 0.02	0.2 ± 0.1	0.8 ± 0.4a	1.7 ± 0.5b
Annual forb	0.3 ± 0.1	0.2 ± 0.1	1.2 ± 0.1	1.4 ± 0.2
Shrub	0.0 ± 0.0	0.01 ± 0.01	0.0 ± 0.0a	1.5 ± 1.1b
Vegetation total	1.0 ± 0.1A	4.0 ± 0.1B	5.6 ± 1.2a	23.2 ± 3.1b
Litter	8.5 ± 1.5A	26.6 ± 2.7B	8.1 ± 1.4a	18.8 ± 2.2b
Rock	6.7 ± 2.4	5.7 ± 2.1	6.3 ± 2.4a	4.6 ± 1.8b
Bare ground	83.9 ± 4.7A	63.6 ± 9.8B	79.9 ± 7.0a	53.3 ± 9.5b

Soil and Vegetation Sampling

Six soil samples were collected from 0–2.50-cm and 2.5–5.0-cm soil depths adjacent to each plot using an open-ended core sampler. Each sample was oven dried and used to determine soil bulk density and gravimetric soil water content. The 6 samples from the 0–2.5-cm soil layer surrounding each plot were combined and subsampled 3 times for determination of particle size by the hydrometer method (Gee and Bauder 1986) and aggregate stability by the vapor-wetting, wet-sieve method (Kemper and Rosenau 1986). Soil organic carbon was determined using a PE2400 CHNS/O analyzer (Perkin-Elmer Corp., Waltham, MA). Prior to soil organic carbon analysis, carbonates were removed as described by Nelson and Sommers (1982).

Understory basal and canopy cover, and surface roughness were sampled immediately prior to application of rainfall simulations. Portable scaffolding was used during measurement of vegetation and surface roughness to minimize soil disturbance of the runoff plots. In each plot, understory basal and canopy cover were estimated inside 24, 0.2-m^2 (40 × 50 cm) frames, spaced 1 m apart, along 6, 4.5-m transect lines. Canopy and basal cover of herbaceous plants, mosses and cryptogamic crusts, litter, rock, and bare ground were estimated visually. Understory plants were organized into 5 functional groups as described by Bates et al. (2000). Functional groups were: 1) Sandberg's bluegrass, 2) tall perennial grasses, 3) perennial forbs, 4) annual grasses, and 5) annual/biennial forbs. Shrub cover was determined by the line intercept method (Canfield 1941).

Soil surface random roughness was estimated along 20 systematic transects of 45 points each per runoff plot. At each point the distance from an arbitrary level line and the ground surface was measured using a transit level and stadia rod with 3-mm increments. Surface random roughness was then calculated as the arithmetic average of the standard deviations for each of the 20 transects.

Roots were sampled using a 10-cm-diameter corer to a depth of 10 cm in the soil profile after completion of simulated rainfall applications. Four subsamples were taken from each treatment replicate. Roots were washed to remove soil and organic matter using a root washer. Roots were dried to a constant weight at 48°C and weighed to determine root biomass and measured for length using an optical root length scanner (Comair Corp., Melbourne, Australia).

Statistical Analysis

The experimental design was a randomized complete block with 8 blocks and 2 treatments. Treatments were cut and juniper woodland controls. Treatment effects on response variables were compared using a 1-way analysis of variance. All statistical analyses were performed using the Statistical Analysis System (SAS Institute 2001). Data were tested for normality and, if necessary, arcsine square root transformations performed to stabilize variances. Back-transformed means are reported. Statistical significance of all tests were set at $P < 0.05$, and mean separations were conducted using Fisher's protected LSD.

RESULTS

Cutting junipers significantly increased total vegetation cover (canopy and basal) and litter cover (Table 2). Canopy and basal cover were about 4 times greater in the cut versus woodland treatment. Cover was also greater in the cut versus woodland treatment for the following functional groups: perennial grasses, annual grasses, perennial forbs, and shrubs (Table 2). The lack of understory cover and litter in woodland intercanopy zones resulted in higher levels of bare ground when compared to the cut treatment.

Soil bulk density, particle-size distribution, and organic carbon content were unchanged by the cutting treatment (Table 3). Rooting characteristics differed slightly between treatments. In the juniper woodlands, roots originated primarily from juniper and in the cut treatment roots were composed primarily of perennial grasses. Root mass was significantly greater in the woodland (Table 3). Root length and root length density were greater in the cut treatment. Root length and root length density data indicate that the cut treatment had more fine roots than the juniper woodland. This likely resulted in the significant increases in random roughness and aggregate stability found in the cut treatment compared to the woodland control (Table 3).

The amount and timing of runoff was dramatically different for the cut treatment compared to the juniper woodland control. Woodlands rapidly produced significant amounts of runoff, while cut plots produced almost no runoff (Table 4; Fig. 2A). All 8 woodland plots began to run off within 16 minutes following the start of rainfall. Four plots began to

Table 3. Mean (± SE) hillslope characteristics for juniper woodland and juniper removed treatments, 2001. Lowercase letters denote significant treatment differences.

	Juniper woodland	Juniper removed
Slope (%)	18.5 ± 2.0	19.2 ± 1.3
Random roughness (m)	0.024 ± 0.007a	0.036 ± 0.012b
Bulk density 0–3 cm ($g \cdot cm^{-3}$)	1.5 ± 0.10	1.52 ± 0.09
Bulk density 3–6 cm ($g \cdot cm^{-3}$)	1.46 ± 0.06	1.51 ± 0.06
Sand (%)	46.0 ± 7.6	45.2 ± 5.3
Silt (%)	38.8 ± 4.6	37.5 ± 3.9
Clay (%)	15.2 ± 4.1	17.3 ± 3.4
Organic carbon (%)	1.82 ± 0.51	1.94 ± 0.71
Aggregate stability (%)	44.8 ± 10.4a	62.7 ± 8.6b
Root mass ($g \cdot m^{-3}$)	214 ± 20 a	130 ± 22b
Root length (cm)	11.8 ± 10.5	14.3 ± 30.9
Root length density ($cm \cdot cm^{-3}$ soil)	0.037 ± 0.005	0.045 ± 0.012

run off after only 2–4 minutes. Only 2 cut plots generated any runoff during the 1-hour rainfall simulation. One cut plot began to run off at 31 minutes and the other at 43 minutes. By the end of rainfall application, the woodland plots were on average 82% ponded (surface saturated), while the cut plots were only 30% ponded.

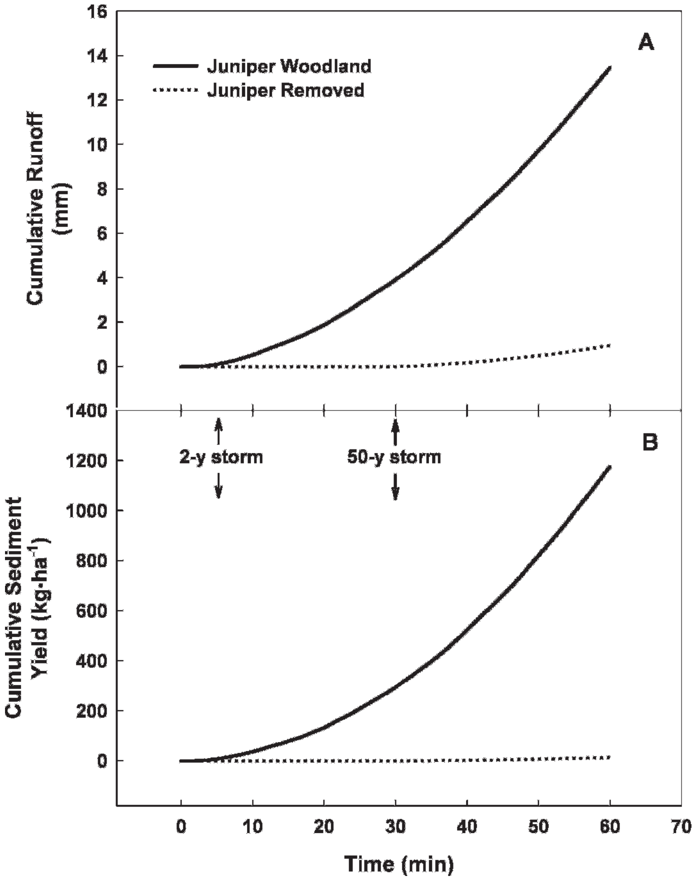

Figure 2. Mean cumulative runoff (**A**) and sediment yield (**B**) for juniper woodland and juniper removed treatments ($n = 8$). Rainfall was applied at 53.5 mm $\cdot$ h^{-1}.

Cumulative sediment yield was 2 orders of magnitude higher for the juniper woodland compared to the cut treatment after 60 minutes of rainfall was applied (Table 4; Fig. 2B). The sediment-to-runoff ratio, a measure closely associated with soil erodibility, was 87.3 and 46.7 $kg \cdot ha^{-1} \cdot mm^{-1}$ for the juniper woodland and cut treatment (only the 2 cut plots that produced runoff were included), respectively. This indicates that soil particles were more easily detached on woodland sites compared to areas in the cut treatment. The juniper woodlands had more bare ground exposed to the soil detachment force of raindrop impact (Table 2). They also had greater surface area exposed to the soil detachment force of overland flow (82% ponded area). In addition, juniper woodland areas had significantly more runoff (Table 4; Fig. 2A) to transport the detached sediment downslope, resulting in a greater total sediment yield.

To help interpret measured differences in runoff and erosion between the juniper woodland and cut treatment, we translated the increasing duration of applied rainfall intensity used in this study (53.5 mm $\cdot$ h^{-1}) into return-period thunderstorms using procedures outlined by Hanson and Pierson (2001) based on long-term weather records from Reynolds Creek Experimental Watershed in southwest Idaho. Based on the assumptions of similarity in site elevations and regional climatic patterns, we used their results to establish return periods for our applied rainfall intensity over 5-, 10-, 15-, 30-, and 60-minute time intervals (Table 4). For example, a 2-year return-period storm would be the equivalent of a storm with a rainfall intensity of 53.5 mm $\cdot$ h^{-1} that lasted 5 minutes and would be expected to occur on average once every 2 years. With the application of a 2-year return-period thunderstorm, 4 juniper plots (50% of the woodland area) produced runoff, while no cut plots produced any runoff. With the application of a 4-year return-period storm, 7 juniper woodland plots (88% of the area) produced runoff, while still no cut treatment plots produced any runoff. A 50-year return-period storm had to be applied before 2 cut plots (25% of the cut area) finally began to produce runoff, while all 8 of the juniper plots (100% of the woodland area) had produced an average of 4 mm of runoff.

Rill discharge was significantly higher for the juniper woodland compared to the cut treatment for all inflow rates tested (Fig. 3A). Values of cumulative discharge were 3 to 7 times higher for the juniper woodland (Table 5). Sediment concentrations within each rill were dramatically higher for the woodland areas compared to the cut areas (Fig. 3B). Sediment-to-runoff ratios were significantly higher for the juniper plots, indicating higher rill erosivities compared to the cut plots (Table 5). The decrease in sediment concentration with increasing inflow rate indicated that rills became detachment limited or armored after being severely eroded (Fig. 3B). Rills in the cut areas remained in more of a transport-limited state because of low rill discharge rates.

A closer examination of rill flow characteristics showed that rills within the juniper woodland flowed downhill over a greater total surface area compared to rills in the cut treatment. The number of flow paths was nearly 50% greater, and the width of flow within each flow path was slightly higher in the juniper woodland compared to the cut areas (Table 5). The depth of flowing water was similar for both treatments, but the water

Table 4. Comparison of mean cumulative runoff and mean sediment yield between juniper woodland and juniper removed treatments for different return-period storms. Uppercase letters denote significant treatment differences between treatments for runoff. Lowercase letters denote significant treatment differences for sediment yield.

			Runoff (mm)		Sediment yield ($kg \cdot ha^{-1}$)	
Time (min)	Rainfall (mm)	Storm return period (y)	Juniper woodland	Juniper removed	Juniper woodland	Juniper removed
5	4.45	2	0.11	0.00	7.9a	0.00b
10	8.89	4	0.53A	0.00B	37.0a	0.00b
15	13.36	8	1.15A	0.00B	78.8a	0.00b
30	26.67	50	3.93A	0.00B	295.0a	0.0b
60	53.34	100+	13.47A	0.96B	1 175.9a	13.8b

velocity was twice as high in the untreated juniper plots (Table 5).

DISCUSSION

While specific inferences drawn from the current study are limited to juniper-affected sites in the intermountain sagebrush steppe, the scope of ecosystem impacts are consistent with woody-plant invasion in other ecosystems around the world. Surface runoff and erosion on semiarid rangeland are generated when high-intensity rainfall rates exceed the infiltration, interception, and surface storage capacities of the soil and vegetation (Wilcox 2002). The specific hydrologic response to high-intensity rainfall is determined by complex interactions between vegetation, soil, and surface characteristics (Pierson et al. 2002). A change in the pattern and density of vegetative cover can alter soil properties and change infiltration and surface runoff patterns (Wood 1988; Roberts and Jones 2000). Greater plant density and dispersion can reduce erosion by providing protection from raindrop impact and by slowing the rate of water flow across the soil (Blackburn et al. 1994). Davenport et al. (1998) suggested that soil erosion rate is a balance between soil erosion potential (SEP) and ground cover condition. Accelerated erosion occurs when ground cover is reduced to a threshold beyond which runoff can move along a continuous flow path through the intercanopy zone. SEP is affected by soil texture and aggregate stability, slope, rainfall intensity, and ground cover.

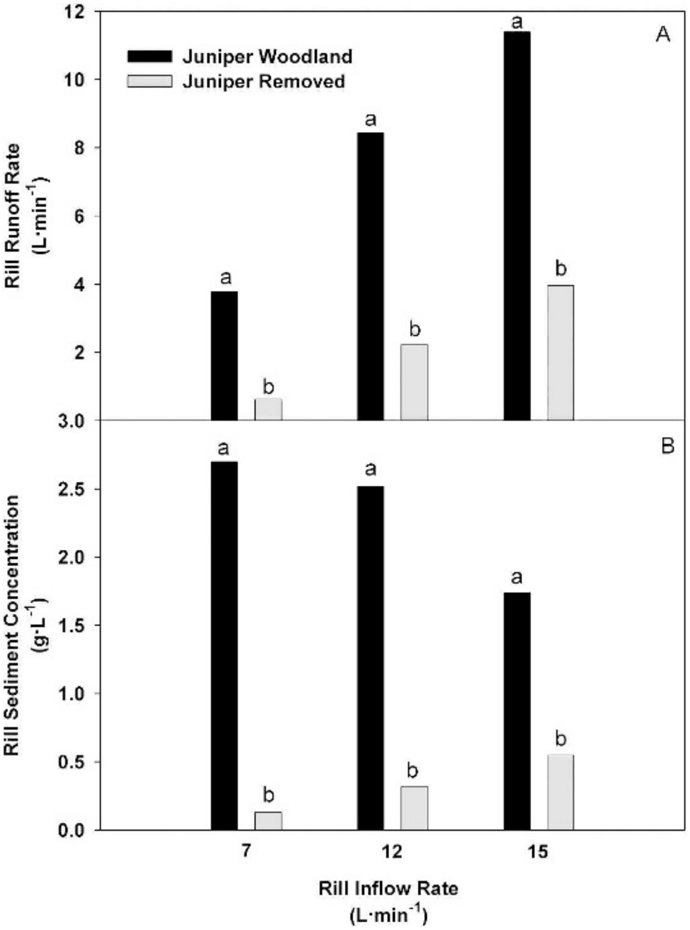

Figure 3. Mean rill discharge rate (**A**) and sediment concentration (**B**) by rill inflow rate for juniper woodland and juniper removed treatments ($n = 8$). Values for the same rill inflow rate with different letters are significantly different ($P < 0.05$).

As junipers become dominant, they reduce understory plants and concentrate ground cover into areas directly below their own canopies (Wilcox 1994). On many juniper-dominated sites, tree canopy cover is between 20% and 35%, leaving up to 80% percent of the area with reduced vegetation or litter cover for protection (Miller et al. 2005). Juniper impacts on understory vegetation are magnified where a restricted soil layer limits rooting depth and increases plant competition for water and nutrients (Bates et al. 2000; Miller et al. 2000). Depleted understory vegetation can also have insufficient fine roots to stabilize the soil and lower levels of soil microtopography, important for surface water storage.

In this study, the juniper cutting conducted in 1991 resulted in significant increases in herbaceous canopy cover by the second year posttreatment (Bates et al. 2000). Canopy cover values stabilized by the second year posttreatment, though plant composition in the interspaces between trees continued to shift from a dominance of Sandberg's bluegrass to more large perennial bunchgrasses (Bates et al. 1998). Removal of juniper trees improved ground cover in the interspaces between trees from 16% to 36% by the end of the study.

The hydrologic impacts of western juniper in this study are consistent with previous studies that have linked changes in infiltration, runoff, and erosion to the decline in understory vegetation, surface litter, and vegetative basal cover that results in larger more interconnected areas of bare ground (Davenport et al. 1998; Reid et al. 1999; Hastings et al. 2003). These results are also consistent with past experiments from other ecosystems that have shown that increased levels of bare

Table 5. Mean rill flow characteristics by rill inflow rate for juniper woodland and juniper removed treatments, 2001.

	Juniper woodland			Juniper removed		
Inflow rate ($L \cdot min^{-1}$)	7	12	15	7	12	15
Cumulative inflow (L)	120	264	444	120	264	444
Cumulative discharge (L)	53.3[1]	154.3[1]	289.9[1]	7.8	35.4	82.5
Cumulative sediment (g)	114.2[1]	368.5[1]	626.8[1]	4.3	35.0	85.3
Sediment/runoff ($g \cdot L^{-1}$)	2.58	2.49	2.21[1]	—[2]	—[2]	0.75
Number of flow paths	2.6	2.7	2.9[1]	—[2]	—[2]	2.1
Flow velocity ($m \cdot s^{-1}$)	—[2]	0.098	0.110[1]	—[2]	—[2]	0.067
Flow depth (mm)	7.7	8.3	8.5	—[2]	—[2]	8.3
Flow path width (m)	0.23	0.24	0.26	—[2]	—[2]	0.22
Total flow width (m)	1.11	1.10	1.13	—[2]	—[2]	0.79

[1] Treatment differences are significant for associated inflow rate.
[2] Insufficient data replication ($n < 4$).

ground can lead to decreased infiltration capacity and greater continuity of overland flow paths (Blackburn and Skau 1974; Blackburn et al. 1992; Pierson et al. 1994; Wilcox et al. 1996; Reid et al. 1999). The high rill erosion rates found in untreated juniper plots in this study were a result of the dramatic increase in velocity of water moving along a greater number of flow paths. Lower ground cover and increased bare ground in the juniper woodland provided less resistance to water moving over the soil surface. Overland flow could then pick up more speed and thus energy for detachment and transport of soil particles in the flow paths. This, coupled with significantly lower infiltration capacity and aggregate stability in the juniper woodland, resulted in greater rill and interrill discharge rates and sediment concentrations.

The specific amounts of runoff and erosion presented in this paper are only representative of processes at the hillslope scale. However, the general conclusion that a significant decline in understory vegetation negatively affects hydrology and erosion holds for varying scales. Infiltration capacity can decrease to the point where a site begins to generate runoff from small thunderstorms that frequently occur. During rare, intense thunderstorms, large amounts of runoff can be generated very quickly. Loss of soil cover and a decrease in soil aggregate stability can leave the soil vulnerable to splash erosion from raindrop impact. Large patches of interconnected bare ground provide better opportunity for runoff to concentrate into rills with high flow velocity, high erosive force, and sediment transport capacity.

MANAGEMENT IMPLICATIONS

This study highlights the importance of maintaining good surface soil cover when managing western juniper encroachment. Juniper-induced reductions in understory vegetation and litter can negatively affect hydrology and erosion to the point where a site begins to generate runoff and erode under frequent small thunderstorms. In this study cutting juniper and allowing site recovery for a 10-year period was very successful at restoring hydrologic stability. Surface soil cover was restored, and infiltration capacity increased sufficiently to protect the site from even large thunderstorms. When runoff was generated, the improved surface soil cover conditions significantly reduced the amount and velocity of overland flow, thereby dramatically reducing rill erosion rates.

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