HYDROLOGIC AND VEGETAL RESPONSES TO FUELWOOD HARVEST AND SLASH DISPOSAL IN A PINYON PINE AND JUNIPER DOMINATED GRASSLAND

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Miscellaneous Report No. M27

October 2001

New MexicoWater Resources Research Institute
In Cooperation with
New Mexico State University

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ABSTRACT

Woodlands dominated by pinyon pine (*Pinus* spp.) and juniper (*Juniperus* spp.) species have expanded both in aerial extent and density during the last century and now occupy 8 to 12 million hectares in the western United States. Accelerated erosion has been observed in many of these former grass and shrublands that are now dominated by pinyon pine and junipers. The objective of this research project was to determine the effects of fuelwood harvesting and slash disposal of a pinyon pine and juniper woodland on understory plant responses, runoff, sediment concentration, and bedload. Five plots (25 x 12 meters) were located in each of four blocks and contained runoff subplots, which were 21.1 x 3.6 meters with a drop box, flume, and sediment sampler at the bottom. Calibration was conducted during 1988. Treatments were applied in 1989 and 1991. Vegetation responses, runoff, sediment concentration, and bedload were measured each monsoon season through 1999 for a total of 10 years. The treatments included: (1) four plots not clearcut (control plots), (2) four plots clearcut and slash completely removed in June 1989, (3) four plots clearcut with slash uniformly scattered in June 1989, (4) four plots clearcut with slash uniformly scattered in June 1989 and burned on October 31, 1989, and (5) four plots clearcut with slash uniformly scattered in June 1989 and burned on November 7, 1991.

The least amounts of runoff and erosion were from (1) plots that were clearcut and had the slash removed in June 1989, (2) plots that were clearcut with the slash homogenously scattered on the plots in June 1989, and (3) plots that were clearcut with the slash homogenously scattered on the plots in June 1989 and burned in November 1991. The slash scatter with no burn treatment started protecting the site immediately after clearcutting. Removing the slash after clearcutting left the plots temporarily exposed, which resulted in high levels of runoff and erosion for a couple of years. However, results during subsequent years were similar to clearcutting with scattered slash.

Key words: runoff, erosion, sediment concentration, bedload, slash, understory

ACKNOWLEDGEMENTS

This project was funded by the New Mexico State University Agricultural Experiment Station. The authors wish to acknowledge the support of the Black Range Ranger District and the Supervisor's Office of the Gila National Forest. Special thanks go to the late Chuck Schipp, the present Ranger Jim Paxon, and soil scientist Charles Souders.

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INTRODUCTION

Woodlands are more openly spaced than forests, their canopies are discontinuous, and they occupy many semiarid regions of the world. A common woodland type in North America is dominated by pinyon pines and juniper trees (*Pinus edulis* Engelm., *Pinus cembroides* Zucc., and *Pinus monophylla* T.& F., and *Juniperus* L. spp., respectively) that extend over an area of more than 8 million hectares in the western United States with large areas also in Mexico and small areas in Canada (Preston 1965). Similar woodlands are found extensively on other continents of the earth.

From 100 to 150 years ago, much of the land in North America that is presently dominated by pinyon pine and junipers was dominated by grasses and shrubs with a widely scattered savannah of trees (Tausch 1999). These grass and shrublands were later invaded and eventually dominated by pinyon pine and juniper trees as a consequence of human activities, particularly by overgrazing with livestock and mostly by fire suppression (Evans 1988). As a consequence, runoff and erosion rates are very low directly beneath the trees because of the deep organic additions to the soil from needle fall. However, fibrous root systems from these trees extend horizontally two and a half times their crown radii into the interspaces between crowns. These roots are near the soil surface, so that they effectively compete with understory shrub, grass, and forb species for soil moisture (Breshears *et al*. 1997) and nutrients (Doescher *et al*. 1987 and Padien and Lajtha 1992). These interspaces are nearly bare, experience high runoff and erosion, and gullies often develop. Sustainability of these lands ultimately depends on the sustainability of the soil resources (National Research Council 1994). The increase in erosion rates on some sites has been so dramatic that the soil resource is lost within decades if the processes are not halted or reversed (Wilcox *et al*. 1996a, 1996b, and Davenport *et al*. 1998).

These woodlands offer certain benefits to humans and their animals, including fuelwood, fence posts, poles, nuts, decorative trees, outdoor recreation, livestock grazing (although less than potential), and habitat for many wildlife species. Harvesting woodlands for these products can simultaneously convert sites back to grass or shrublands, which should decrease flood runoff and erosion. However, under their current condition, these woodlands seldom provide a dependable water supply for downstream users. When considering vegetational conversion, hydrological responses must be given particular attention because of the potential for induced flooding and sediment loading. Replacing vegetation is a very sensitive operation from a hydrological standpoint (Wood 1988). A primary consideration of vegetation conversion should always be soil and water conservation.

This research program reflects an effort to reduce soil erosion and improve other hydrological attributes through the simple techniques of slash management associated with tree harvesting. In the past on many areas, slash (limbs and needles) has been piled and burned following stem removal. This resulted in a sterile soil that lasted for about 10 years and the first thing to grow on a site was usually sparse vegetation, which encouraged an undesirable gully that lasted for several decades. Recently, the stem wood of the tree plus the slash have been removed from sites in western New Mexico to make fuel by grinding the wood and slash and forming fuel pellets (Romo 2000). The pellets are then burned in stoves and furnaces. In central New Mexico, whole juniper trees are chipped and combined with plastic to make signs, posts, and boards (Kaplan 2000). The effects of fuelwood harvesting and slash disposal on runoff, sediment concentration, bedload, and understory plant responses were studied. Inferences drawn from these studies can be used to determine the most reasonable management strategies to minimize flooding and accelerated soil erosion, and increase livestock and wildlife forage production.

STUDY AREA

Location and Configuration

The study site was in a commercial fuelwood harvesting area of a pinyon pine and juniper woodland in west central New Mexico, adjacent to Spring Mesa in Section 36, T9S R12W, Catron County, New Mexico. The mean elevation was 2,245 meters. The experimental site extended over an area of about 20 hectares on three north to south ridges that join on the north end with a mesa. In 1986, four replications of five runoff plots, each 22.1 meters long and 3.6 meters wide, were established to measure hydrological responses to fuelwood harvesting. The slope of runoff plots (5% to 8%) was quite uniform within the blocks but varied slightly between blocks.

Soils

Soils on the site are Lithic Haplustalfs, having a thin surface layer of reddish-brown non-calcareous gravelly loam over reddish-brown gravelly clay or heavy gravelly clay loam to a depth of 30 cm to 90 centimeters (Javed 1991). This means they have an ochric epipedon, an argillic horizon, and moderate to high base saturation, and water is held at <15 bars tension during at least 3 months each year when the soil is warm enough for plants to grow. The soils are <50 cm deep and moisture moves through the soil to deeper layers only in occasional years.

Climate

Mean maximum and minimum annual temperatures are 19^{o}C and $^{-}1.7^{o}$C, respectively. Mean annual precipitation is 319 mm with about 111 frost-free days from June 5 through September 24. Limited precipitation in the form of snow is experienced during December and January. The driest part of the year is usually April, May, and June. Substantial precipitation is received as short-lived summer rains of mild to moderate intensity (Javed 1991) from July through September. October and November are often dry until winter precipitation arrives. On-site climatic data for the growing season from 1989 through 1999 included precipitation.

Vegetation

Vegetation in the study area consisted of a moderately low tree density of two-needle pinyon *(Pinus edulis* Engelm.) and alligator juniper (*Juniperus deppeana* Steud.). Both pinyon pine and alligator juniper tended to be active reproductively. Scattered throughout, gray oak (*Quercus grisea* Liebm.) was the only hardwood species and no shrubs were present. The herbaceous growth was comprised of a variety of grass and forb species.

Among grasses, the most plentiful species were:

Poverty threeawn	*Aristida divaricata* Willd.
Pine dropseed	*Blepharoneuron trichloepis* (Torr.) Nash
Blue grama	*Bouteloua gracilis* (H.B.K.) Lag. Es Steud.
June grass	*Koeleria cristata* Pers.
Wolftai	*Lycurus phleoides* H.B.K.
Longtongue muhly	*Muhlenbergia longiligula* Hitchc.
Mountain muhly	*Muhlenbergia montana* (Nutt.) Hitchc.
Pine ricegrass	*Piptochaetium fimbriatum* (H.B.K.) Hitchc.
Little bluestem	*Schizachyrium scoparium* (Michx.) Nash
Nash squirreltail	*Sitanion hystrix* (Nutt.) J.G. Smith

The common forb and sedge species included:

Milkvetch	*Astragalus* L. spp.
Sedge	*Carex* L. spp.
Day flower	*Commelina dianthifolia* Delile
Indigobush	*Dalea* L. spp.
Fleabane	*Erigeron* L. spp.
Wright buckwheat	*Eriogonum wrightii* Torr.
Slender goldenweed	*Haplopappus gracilis* (Nutt.) Gray
Pepperweed	*Lepidium* L. spp.
Mustard	*Sisymbrium linearifolium* (Gray) Payson
Golden eye	*Viquiera dentata* (Cav.) Spreng.

The sparse understory cover and the high proportion of bare soil contribute to highly erodible soil conditions.

METHODS

In 1986, twenty experimental plots were established in an area where commercial fuelwood harvesters removed pinyon pine and juniper. Five plots were located in each of four blocks. These experimental units were 25 x 12 meters and contained runoff plots that were 21.1 x 3.6 meters or 0.081 hectare. These plots were the same length and twice as wide as the plots used to develop the Universal Soil Loss Equation (Wischmeier 1976), which is widely used on croplands. The wider width was used because rangeland soils and vegetation tend to be more heterogeneous than croplands, and the wider width is needed so that differences are not partitioned but an overall and representative effect is achieved (Wood *et al*. 1993). The runoff plots were bordered with sheet metal strips that were buried 10 cm below the soil surface and were 20 cm high above.

At the downslope side of each runoff plot, a drop box, approach box, H-flume, stage recorder, and Coshocton wheel sediment sampler were located (Brakensiek *et al*. 1979). The plots were arranged in a Randomized Complete Block Design. Prior to assigning the intended treatments, these plots were used to collect preliminary data on runoff, sediment yield, and phytomass production during the growing season of 1988. The objective was to determine variations among the plots under undisturbed natural conditions. The data showed no significant differences within the blocks but some slight differences between blocks. Because three ridges were used for plot locations, a weighing-type precipitation gage was located on each ridge (Brakensiek *et al*. 1979).

Precipitation, runoff, and suspended sediment data were collected weekly from the first of June through September. Sampling was conducted during this time period because this is when most of the precipitation occurs that results in runoff and erosion. Bedload and vegetation production data were collected at the beginning of October, which is at the end of each growing season. Bedload consisted of soil particles in the runoff that were too heavy to be suspended. They collected in the drop and approach boxes above the flumes. Vegetation sampling consisted of clipping grasses and forbs on 10 randomly located 0.5 m^2 plots down to 1 cm height, air drying the samples in an oven at 60^o C for one week, and weighing the dried samples.

The treatments included:

(1) four plots not clearcut (control plots),

(2) four plots clearcut and slash completely removed in June 1989,

(3) four plots clearcut with slash uniformly scattered in June 1989,

(4) four plots clearcut with slash uniformly scattered in June 1989 and burned on October 31, 1989,

(5) four plots clearcut with slash uniformly scattered in June 1989 and burned on November 7, 1991.

Eight plots were burned in an effort to control sprouting from juniper stumps. Sprouting often results in a re-infestation of juniper trees within a few years. Climatic conditions during the 1989 burn included: air temperature of 10^{o} C, relative humidity of 40%, and wind at 4.8 km h^{-1}. Climatic conditions during the 1991 burn included: air temperature of 14^{o} C, relative humidity of 35%, and wind at 12.9 km h^{-1}. Each experimental unit included a runoff plot and an adjacent 4-meter-wide strip to allow destructive vegetation and soil sampling.

Overall differences among treatments and within the treatments for different hydrologic and vegetal variables were tested using analysis of variance (ANOVA) by the GLM procedure (SAS 1985) at the 0.10 significance level. If the F-test in the ANOVA was found significant at this alpha level, then pairwise tests on least square means were conducted using the predicted difference option to separate the treatment differences.

RESULTS AND DISCUSSION

Precipitation

During the sampling periods, precipitation during June was usually low (Figure 1). Precipitation during July, August, and September was quite variable as were yearly differences. Drought years were 1989, 1992, 1994, 1995, 1996, and 1998 with 1989, 1994, and 1996 being the most severe. Droughts are defined in general terms as unusually severe and extended periods of low precipitation, often accompanied by high temperatures and low humidity (Black 1996). These severe droughts were characterized by relatively dry winters and long, dry spring seasons. The five years before 1989 (1984 through 1988) were above normal in precipitation. August was the wettest month in six of the 12 years followed by July in five and September in one of the 12 years.

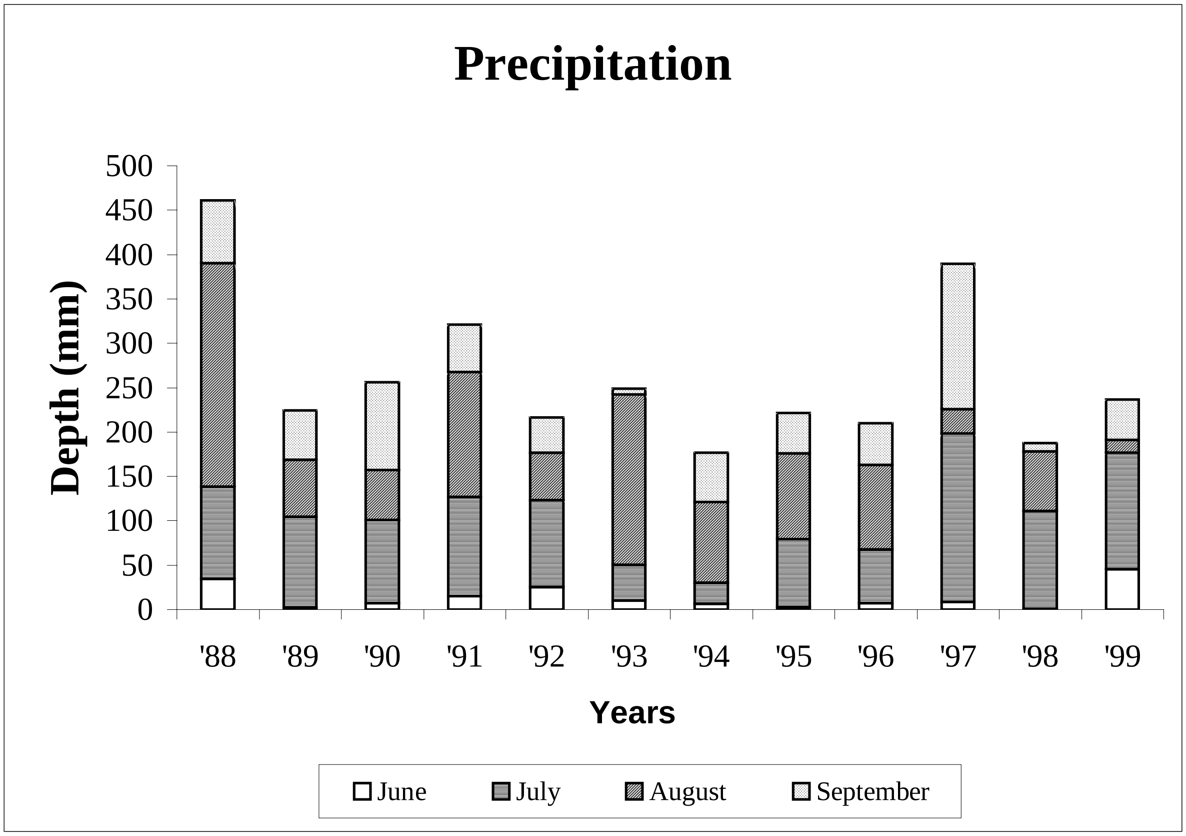

Figure 1. Total monthly precipitation (mm) for June through September, 1988-1999.

Since all plots received the same amount of precipitation within a growing season and the soils were the same for all plots, vegetal responses and hydrologic differences are attributed to treatment effects. However, interpreting results among years is difficult because of yearly differences in precipitation.

Vegetation

Three environmental factors most influenced understory production. These included monthly or seasonal precipitation, overstory competition, and burning. When the overstory was removed, the understory responded to precipitation and burning. The lack of an overstory resulted in greater soil moisture, greater soil nutrient availability, and greater solar radiation to fuel understory plant growth. Annual forbs and perennial grasses were the predominant understory plants. This response in understory plant growth in turn affected the amounts of runoff, sediment concentration, and bedload, as discussed below.

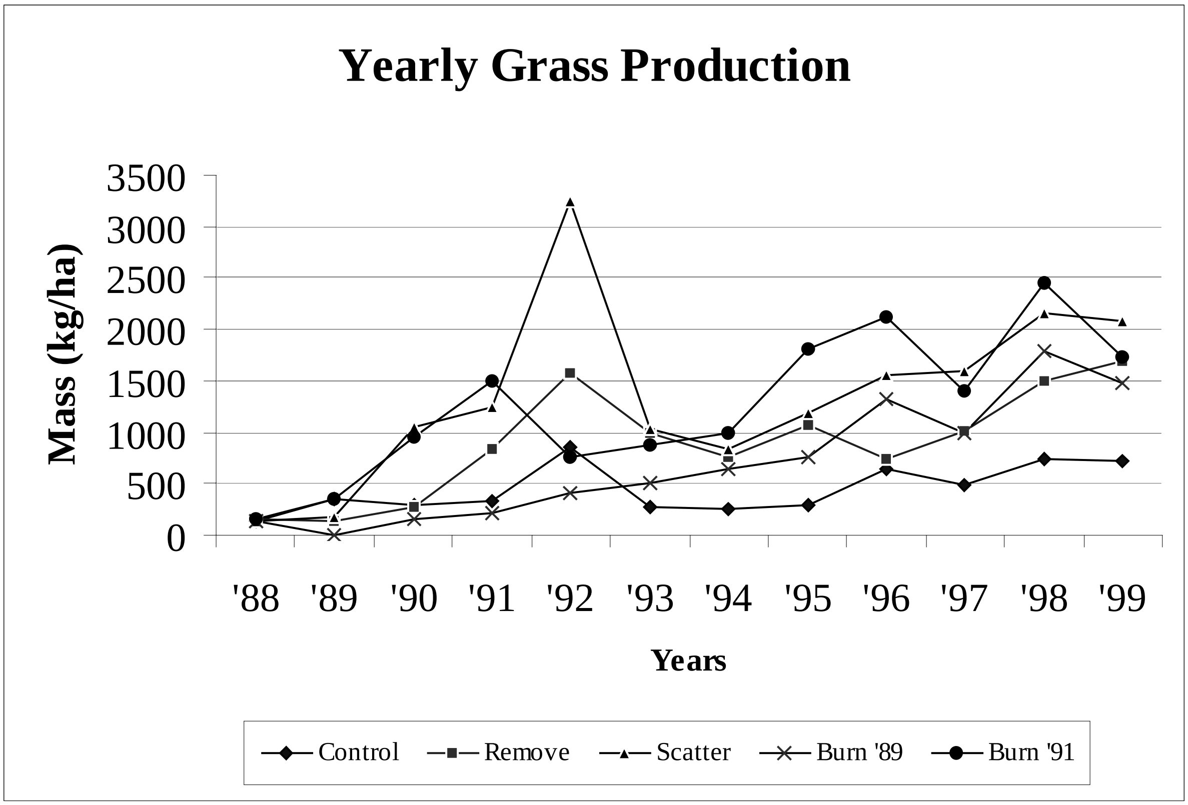

Figure 2. Mean grass production (kg ha^{-1}) for each slash disposal treatment and year.

The greatest grass production in the first few years following treatment was on plots that were clearcut with the slash scattered with no subsequent burning (Figure 2 and Appendix Table 1). There was a significant lag time for grass production on plots that were burned in 1989. Production on all plots was low during the severe drought period in 1994, but the burn in 1991 and scatter treatments had grass production levels that were greater than the control. Grass production on all plots increased for the last five years of the study over the controls.

The total amount of forbs as expressed by phytomass at the end of the growing season increased most dramatically in the plots that were burned in 1989 (Figure 3 and Appendix Table 2). Plots for the other treatments also had forb production levels that were greater than the control plots with marked differences in some years (1990 and 1997).

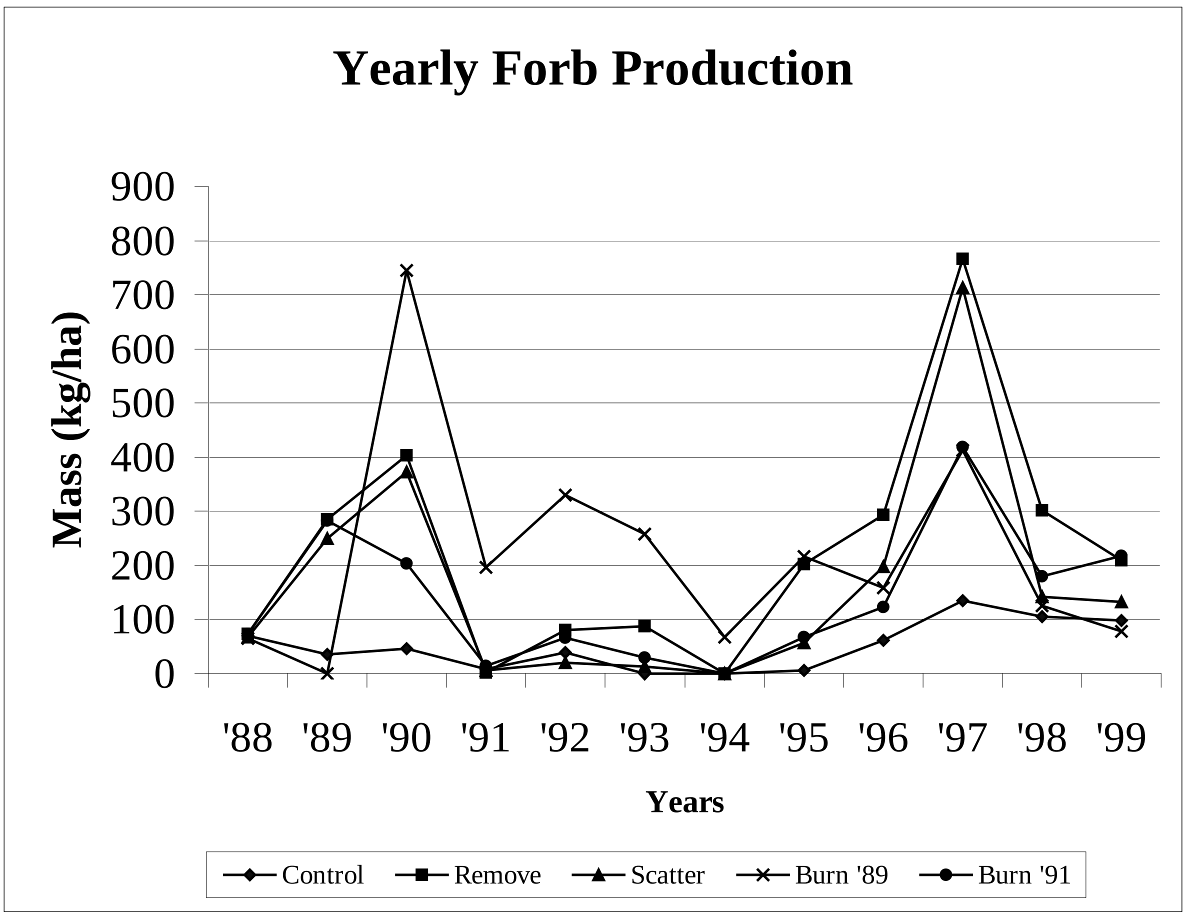

Figure 3. Mean forb production (kg ha^{-1}) for each slash disposal treatment and year.

Except for the plots that were clearcut and burned in 1989 and had a large forb component, total plant production closely paralleled perennial grass production (Figure 4 and Appendix Table 3). Throughout the study, the site was excluded from domestic livestock (*Bos* spp.), but the site was used by wild animals such as elk (*Cervus canadensis*), deer (*Odocoileus hemionus* and *O. virginicus*), and rabbits (*Lepus* spp. and *Sylvilagus* spp.). It was evident in the plots with scattered slash that the slash protected the forage species (forbs and grasses) from utilization by large ungulates until the responses from loss of overstory competition could be realized.

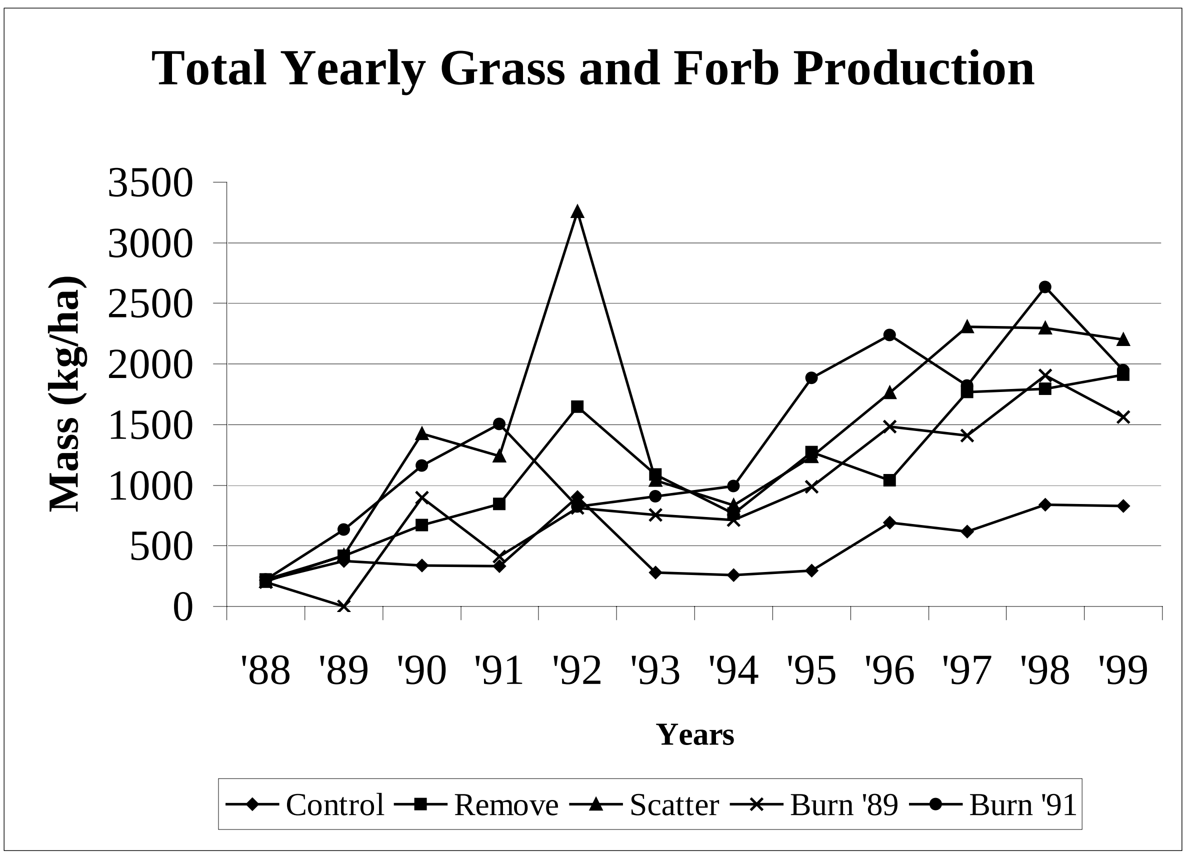

Figure 4. Mean total grass and forb production (kg ha^{-1}) for each slash disposal treatment and year.

The proportion of grasses to forbs by weight decreased the first year after clearcutting (Figure 5). The proportion of grasses to forbs in plots with the slash removed remained lower than the controls and plots in scatter and burn in 1991 treatments for two years, while plots that were burned in 1989 remained lower than the controls and plots of other the treatments for seven years. Therefore, biodiversity as indicated by the grass/forb ratio of production was increased by burning in October after clearcutting in June. However, hydrologic responses to this treatment did not how this to be desirable overall, and is discussed below.

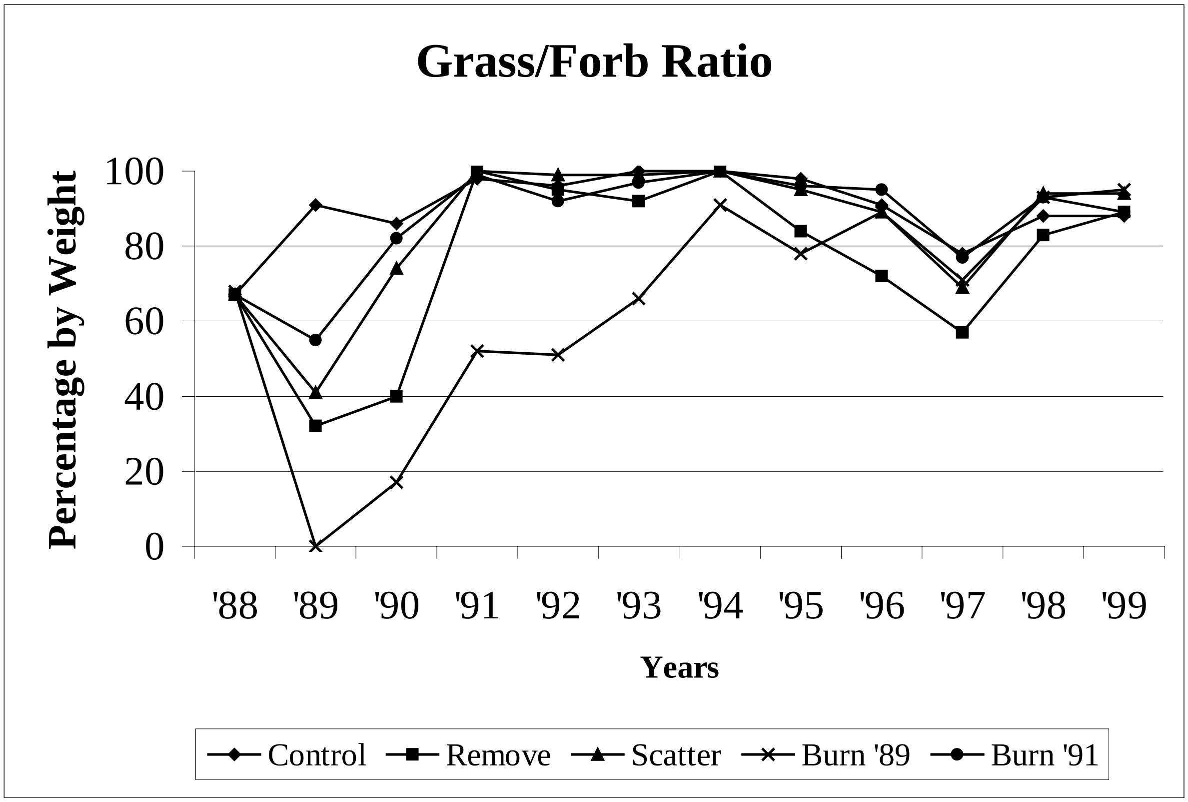

Figure 5. Ratio of grass/forb production (%) for each slash disposal treatment and year.

Runoff

The 20 plots were assigned treatments in 1988, but treatments were not applied until June and October 1989 and November 1991. These assignments allowed for calibration and determination of pre-treatment differences. No pre-treatment differences were found from runoff collected in 1988 (Figure 6 and Appendix Table 4). Only three treatments had been completed during the growing season. These included (1) four plots not clearcut (control plots), (2) four plots clearcut in June 1989 and slash completely removed, and (3) twelve plots clearcut in June 1989 with slash uniformly scattered.

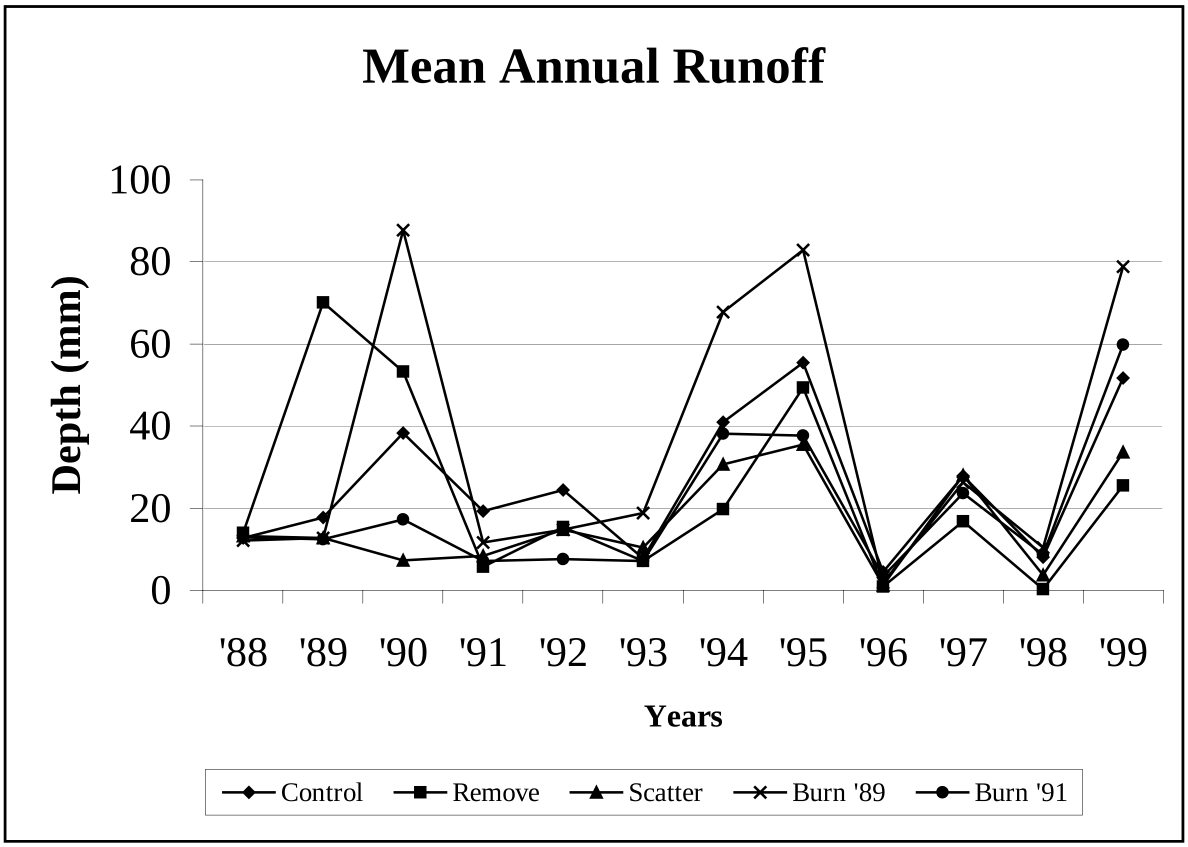

Figure 6. Mean runoff (mm) from each runoff producing storm for each slash disposal treatment and year.

Runoff from plots that had slash permanently scattered and plots burned in 1991 was lower or similar to runoff from control plots (Figure 6). Runoff from plots that had slash removed and plots burned in 1989 was higher or similar to runoff from control plots for two years. This is attributed to these plots having no protection from trees and little understory influence because the understory did not have enough time to respond to overstory removal. Some of the increased runoff may be due to decreased rainfall interception. Because understory plants had not responded much during this growing season, decreased interception from tree harvest was probably not off-set by increases in understory growth and understory interception as has been observed in other studies (Wood 1988). After two years, runoff from plots that had slash removed was lower or similar to runoff from control plots.

Four of the twelve plots that were clearcut with slash scattered in June 1989 were burned in November 1991. In 1992, runoff from these plots was lower than runoff from the control plots (Figure 6). This is a result that is quite different from the plots that were burned in 1989, which was only four months after clearcutting. The plots that were clearcut in June 1989 and burned in November 1991 had 28 months for the understory to increase, which protected the site during burning. Runoff from the plots that were burned in 1989 was high in 1994 and 1995, and statistically significantly higher than the control and other treatments in 1999. This shows that this treatment had high runoff rates 10 years after application.

Sediment Concentration

No pre-treatment differences were found from sediment concentration in runoff collected in 1988 (Figure 7 and Appendix Table 5). These levels were considerably higher than the following 11 years and may be due to disturbances from plot installation. Most importantly, sediment concentration from all five treatments was similar and nearly identical.

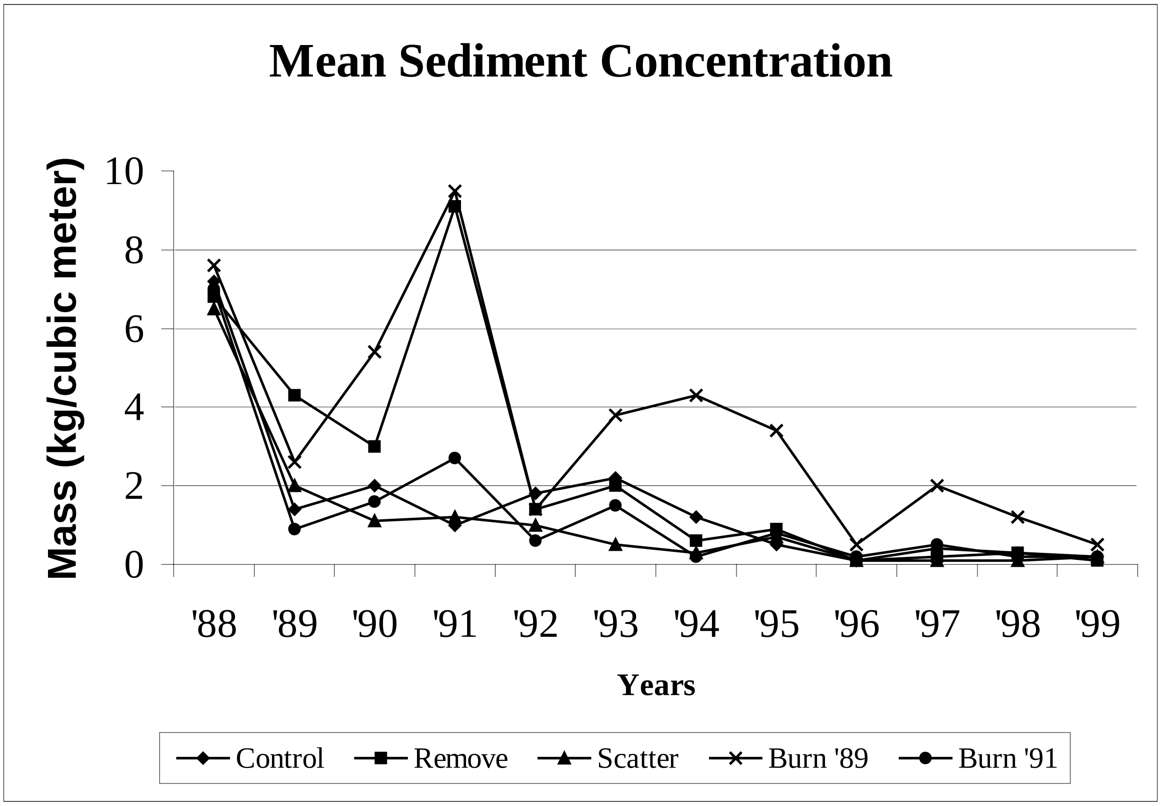

Figure 7. Mean sediment concentration (kg meter [3 -1]) from each runoff producing storm for each slash disposal treatment and year.

Sediment concentration in runoff from plots that had slash permanently scattered and plots burned in 1991 was lower or similar to sediment concentration from control plots (Figure 7). Sediment concentration in runoff from plots that had slash removed and plots burned in 1989 was higher or similar to sediment concentration from control plots for two years. As for runoff, this is attributed to these plots having no protection from trees and little understory influence because the understory did not have enough time to respond to overstory removal. After three years, sediment concentration in runoff from plots that had slash removed was lower or similar to runoff from control plots. Sediment concentration values from the plots that were burned in 1989 were statistically significantly higher than from control and other treatment plots in 1994, 1995, and 1997 (Appendix Table 5).

Bedload

No significant pre-treatment differences were found for cumulative bedload collected in 1988 (Figure 8 and Appendix Table 6). Bedload values from the control plots were higher than from the 12 plots that were clearcut with slash uniformly scattered in 1989 (Figure 8). However, more bedload was received from plots that were clearcut and slash completely removed than from the controls. As for runoff and sediment concentration, this is attributed to these plots having no protection from trees and little understory influence because the understory did not have enough time to respond to overstory removal.

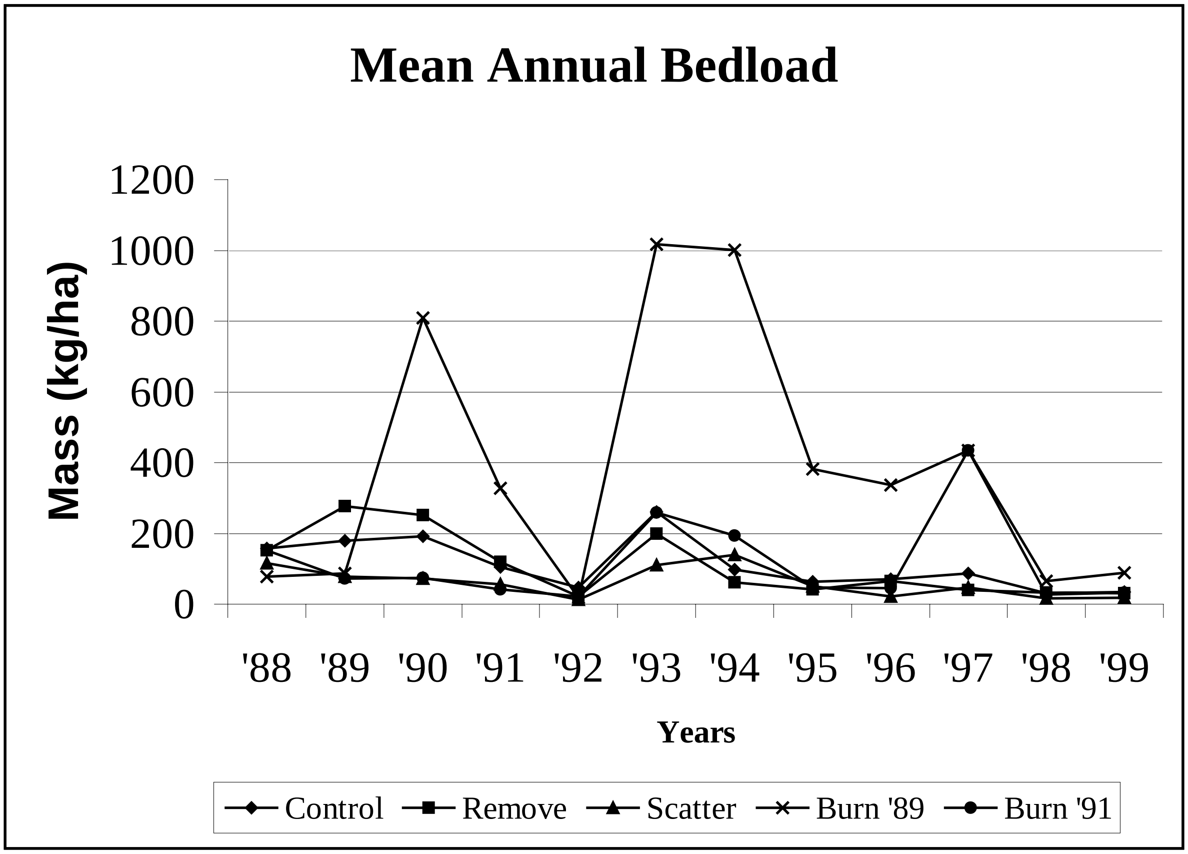

Figure 8. Mean cumulative bedload (kg ha^{-1}) for each slash disposal treatment and year.

The first effects of burning on bedload values were found in 1990 (Figure 8). Bedload increased slightly from 1988 through 1990 on control plots and slightly decreased from 1989 through 1990 on plots that were clearcut with their slash scattered. As for runoff and sediment concentration, this is attributed to increased understory growth as a result of removing competition by trees. Plots that had been clearcut and slash removed had less bedload in 1990 than plots that had been burned the previous October. These burned plots had bedload values that were nearly four times bedload values found in the control plots. Like plots that were clearcut with slash completely removed, a lag time existed where no protection by trees was given to the plots. Also above-ground phytomass of the understory was gone, and the understory did not have enough time to respond to the loss of tree competition.

In 1991, plots that were clearcut with slash completely removed had about the same bedloads as the control plots (Figure 8). The most remarkable result is that bedload values from plots that were burned in October 1989 had decreased from high levels in 1990 to levels that were closer to the controls. Plots that were clearcut with slash scattered continued to have bedload values less than the controls.

Low bedload values came from all plots in 1992 (Figure 8). Bedload was greatest from plots that were burned in 1991. Bedload values were not nearly as high following the 1991 burn as those that followed the 1989 burn.

In 1993, bedload values were significantly highest from the plots that were burned in 1989. Bedload values for the control plots and plots that were burned in 1991 were similar. The plots burned in 1989 and to a lesser extent, the plots burned in 1991 had an increased population of ground dwelling rodents such as pocket gophers (*Chaetodipus* spp.). Each of the 1989 burned plots had soil mounds on about 10 to 15% of the plot area. These mounds consisted of excavated soil that was readily eroded and carried off the plots. Much of the bedload on the burned plots is attributed to these mounds. The bare soil of the burned plots is more exposed to air temperature changes than the unburned plots. The wide range of temperatures resulted in shrinking and swelling of the soils, which further results in lower soil bulk densities. The soils with lower bulk densities are probably more suitable for ground rodents than the more compacted soils found on the unburned plots.

After 1992, bedload from plots burned in 1991 continued to decrease to levels similar to the control, slash removed, and slash scattered plots except in 1997 when values were elevated again.

CONCLUSIONS

Overall, the least amounts of runoff and erosion were from (1) plots that were clearcut and had the slash removed in June 1989, (2) plots that were clearcut with the slash homogenously scattered on the plots in June 1989, and (3) plots that were clearcut with the slash homogenously scattered on the plots in June 1989 and burned in November 1991.

The slash scatter with no burn treatment started protecting the site immediately after clearcutting. Removing the slash after clearcutting left the plots exposed for a couple of years, which resulted in high levels of runoff and erosion. However, results eventually were similar to clearcutting with scattered slash. Plots in these two treatments did not receive any additional treatments to control resprouting. How long it will take these plots to revert to an ecological situation similar to the controls is not known. It is known that by 1993 or four years after clearcutting, the juniper resprouts were up to 1 meter tall with annual growth increasing each year. By 1999, juniper resprouts were up to 2 meters tall. Burning four months after clearcutting to kill resprouts was too soon because the understory did not have enough time to increase in vigor before being burned. Burning 28 months after clearcutting controlled resprouts and gave the site ample time to respond to the clearcut.

The success of the clearcut with scattered slash relative to decreased runoff and erosion is attributed to several reasons. The slash increased surface roughness, which slows runoff velocities and increases runoff path lengths (Sanchez and Wood 1987). The large amounts of understory in areas where the slash was scattered and not burned compared to other clearcut areas may have increased evapotranspiration, which would leave the soil drier with higher infiltration rates.

Similarly, Weltz and Wood (1986) at Fort Stanton, New Mexico found the lowest soil moisture contents were in a livestock exclosure (8.6%) and a rested pasture in a grazing system (6.9%). A moderately stocked, continuously grazed pasture had 8.8%, a heavily stocked, continuously grazed pasture had 9.0%, and a pasture that had just been grazed in a rapid rotation, short duration system had 12.4% soil moisture. A lot of phytomass uses substantial water, which leaves the soil drier than the soil with few plants so that the soils with the most plants have the highest infiltration rates (Wood 1988).

Decomposition of the slash results in colloidal-size organic matter being added to the soil. This organic matter is a building block of soil aggregates, and increased soil aggregation results in increased porosity and infiltration (Wood *et al*. 1987). The plots that were clearcut and burned in 1989 had large amounts of annual forbs in 1990. These are in a lower seral stage than perennial grasses, but have greater biodiversity. High seral stages have been recognized as having lower runoff and erosion than low seral stages (Wood 1988). Therefore, greater biodiversity is not necessarily an indicator of ecosystem health or sustainability.

The treatment of clearcutting with uniform scattering of slash led to the lowest runoff and erosion rates of all treatments including the untreated controls. This treatment gives increased soil water for on-site plant growth and groundwater recharge. The treatment is simple with minimal extra time required for implementation following clearcutting. It does not, however, control resprouts, which could eventually re-dominate the site. But follow-up treatments of individual tree grubbing, burning, and chemical control are possible.

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APPENDIX

Table 1. Mean annual grass production (kg ha^{-1}) for each treatment.

Year	No Cut Control	Clear Cut & Clear Slash 1989	Clear Cut & Scatter Slash 1989	Clear Cut & Burn Slash 1989	Clear Cut 1989 & Burn Slash 1991
	Treatment				
1988	145 a[1]	149 a	140 a	138 a	150 a
1989	341 a	134 a	175 b	0 c	351 a
1990	292 b	268 b	1,053 a	150 b	956 a
1991	326 c	842 b	1,236 ab	216 c	1,493 a
1992	864 b	1,568 a	3,239 a	414 b	756 b
1993	280 b	1,000 a	1,029 a	496 ab	880 ab
1994	260 b	765 ab	835 a	644 ab	993 a
1995	289 c	1,070 abc	1,177 ab	768 bc	1,818 a
1996	632 c	745 bc	1,563 ab	1,323 abc	2,116 a
1997	482 c	1,004 abc	1,595 a	996 bc	1,403 ab
1998	738 b	1,492 ab	2,155 a	1,781 a	2,452 a
1999	729 b	1,700 a	2,072 a	1,485 a	1,728 a

[1]Means followed by the same letter within a year (row) are not significantly different at the 0.10 level of probability as determined by a Least Significant Difference mean separation test.

Table 2. Mean annual forb production (kg ha^{-1}) for each treatment.

Year	Treatment: No Cut Control	Clear Cut & Clear Slash 1989	Clear Cut & Scatter Slash 1989	Clear Cut & Burn Slash 1989	Clear Cut 1989 & Burn Slash 1991
1988	70 a[1]	73 a	68 a	65 a	73 a
1989	35 a	285 a	250 a	0 b	283 a
1990	46 c	403 b	372 b	745 a	204 bc
1991	8 b	2 b	6 b	196 a	14 b
1992	39 b	81 b	20 b	330 a	66 b
1993	0 a	88 a	13 a	258 a	30 a
1994	0 a	0 a	0 a	67 a	0 a
1995	6 b	202 a	57 ab	217 a	67 ab
1996	62 b	293 a	197 ab	159 ab	123 b
1997	135 c	766 a	713 a	413 b	419 b
1998	105 b	301 a	142 b	125 b	180 b
1999	98 bc	209 ab	132 abc	78 c	218 a

[1]Means followed by the same letter within a year (row) are not significantly different at the 0.10 level of probability as determined by a Least Significant Difference mean separation test.

Table 3. Mean annual total plant production (kg ha^{-1}) for each treatment.

Year	Treatment: No Cut Control	Clear Cut & Clear Slash 1989	Clear Cut & Scatter Slash 1989	Clear Cut & Burn Slash 1989	Clear Cut 1989 & Burn Slash 1991
1988	215 a[1]	222 a	208 a	203 a	223 a
1989	376 a	418 a	424 a	0 b	634 a
1990	338 d	670 cd	1,160 ab	895 bc	1,425 a
1991	333 d	844 bc	1,241 ab	412 cd	1,507 a
1992	903 c	1,649 b	3,259 a	815 c	821 c
1993	280 b	1,088 a	1,042 a	754 ab	910 ab
1994	260 b	765 ab	835 a	711 ab	993 a
1995	294 c	1,272 ab	1,234 ab	985 bc	1,885 a
1996	694 c	1,038 bc	1,761 ab	1,481 abc	2,239 a
1997	617 c	1,770 ab	2,308 a	1,409 bc	1,822 ab
1998	842 b	1,793 ab	2,297 a	1,906 a	2,632 a
1999	827 b	1,909 a	2,203 a	1,563 a	1,946 a

[1]Means followed by the same letter within a year (row) are not significantly different at the 0.10 level of probability as determined by Fisher's Least Significant Difference mean separation test.

Table 4. Mean annual runoff depth (mm) for each treatment.

Year	Treatment				
	No Cut Control	Clear Cut & Clear Slash 1989	Clear Cut & Scatter Slash 1989	Clear Cut & Burn Slash 1989	Clear Cut 1989 & Burn Slash 1991
1988	12.70 a[1]	13.97 a	13.21 a	12.19 a	12.95 a
1989	17.78 b	70.10 a	12.70 c	12.70 c	12.45 c
1990	38.35 c	53.34 b	7.37 e	87.63 a	17.27 d
1991	19.35 a	5.81 b	8.38 b	11.68 b	7.11 b
1992	24.52 a	15.48 b	14.73 b	14.73 b	7.62 c
1993	7.74 b	7.10 b	10.41 b	18.80 a	7.11 b
1994	40.96 a	19.85 a	30.65 a	67.79 a	38.10 a
1995	55.41 a	49.36 a	35.56 a	82.87 a	37.63 a
1996	4.44 a	0.95 a	1.27 a	1.90 a	3.49 a
1997	27.84 a	16.88 a	27.97 a	26.35 a	23.66 a
1998	8.04 a	0.32 b	3.81 b	10.48 a	8.74 a
1999	51.65 ab	25.57 b	33.58 b	78.74 a	59.86 ab

[1]Means followed by the same letter within a year (row) are not significantly different at the 0.10 level of probability as determined by a Least Significant Difference mean separation test.

Table 5. Mean annual sediment concentration (kg m^{-3}) for each treatment.

Year	Treatment				
	No Cut Control	Clear Cut & Clear Slash 1989	Clear Cut & Scatter Slash 1989	Clear Cut & Burn Slash 1989	Clear Cut 1989 & Burn Slash 1991
1988	7.2 a[1]	6.8 a	6.5 a	7.6 a	7.0 a
1989	1.4 bc	4.3 a	2.0 bc	2.6 b	0.9 c
1990	2.0 b	3.0 b	1.1 b	5.4 a	1.6 b
1991	1.0 b	9.1 a	1.2 b	9.5 a	2.7 b
1992	1.8 a	1.4 a	1.0 ab	1.4 a	0.6 b
1993	2.2 a	2.0 a	0.5 b	3.8 a	1.5 ab
1994	1.2 b	0.6 b	0.3 b	4.3 a	0.2 b
1995	0.5 b	0.9 b	0.7 b	3.4 a	0.8 b
1996	0.1 b	0.1 b	0.1 b	0.5 a	0.2 ab
1997	0.4 b	0.2 b	0.1 b	2.0 a	0.5 b
1998	0.3 b	0.3 b	0.1 b	1.2 a	0.2 b
1999	0.2 a	0.1 a	0.2 a	0.5 a	0.2 a

[1]Means followed by the same letter within a year (row) are not significantly different at the 0.10 level of probability as determined by a Least Significant Difference mean separation test.

Table 6. Mean annual bedload (kg ha^{-1}) for each treatment.

Year	Treatment				
	No Cut Control	Clear Cut & Clear Slash 1989	Clear Cut & Scatter Slash 1989	Clear Cut & Burn Slash 1989	Clear Cut 1989 & Burn Slash 1991
1988	158 a[1]	152 a	116 a	78 a	152 a
1989	180 b	277 a	78 c	87 c	72 c
1990	192 b	252 b	72 b	809 a	74 b
1991	105 b	119 b	56 b	327 a	42 b
1992	47 a	21 ab	12 b	18 ab	22 ab
1993	261 ab	200 b	110 b	1,018 a	259 ab
1994	97 b	62 b	139 b	1,001 a	194 b
1995	64 b	42 b	50 b	382 a	47 b
1996	71 b	65 b	21 b	336 a	45 b
1997	87 a	40 a	47 a	434 a	434 a
1998	31 ab	33 ab	17 b	65 a	28 ab
1999	35 ab	31 ab	18 b	88 a	33 ab

[1]Means followed by the same letter within a year (row) are not significantly different at the 0.10 level of probability as determined by a Least Significant Difference mean separation test.