Hydrology, Erosion, Plant, and Soil Relationships after Rangeland Wildfire

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Abstract: Wildfire is an important ecological process and management issue on western rangelands. Fire suppression activities in the past century have increased the number and severity of wildfires, resulting in increased soil erosion and decreased water quality. Many infiltration studies on rangeland have shown that litter and vegetation cover protect the soil and enhance infiltration. After fire, water repellency is typically found on the soil surface or a few centimeters below and is also common on unburned rangelands and dry soils conditions. However, the causal agents of water repellency are different for burned and burned conditions. Rainfall simulation studies were conducted for 3 consecutive years immediately following a catastrophic wildfire in Denio, Nevada, in 1999. Study sites were chosen on north-facing hillslopes (35 to 40 percent slope) where the vegetation was dominated by mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*). The objective of this study was to use indirect gradient analysis on the 1999 data to evaluate and summarize pertinent relationships between vegetation, soil, topographic features, infiltration, runoff, sediment production, and microsite distinction (shrub coppice and interspace) on burned and unburned areas. The first ordination (strategy 1) used four infiltration parameters and the results were unexpected. In the multivariate context, higher infiltration trends were associated with the burned treatment compared to the unburned treatment. Water repellency on the burned sites was apparent at the soil surface; however, it appears that repellency was also a significant factor on the unburned area. Water repellency in the unburned treatment was likely caused by assorted litter buildup (up to 11,605 kg/ha) in > 80-year stands (sagebrush duff and grass in the shrub coppice areas and grass litter in the interspace). The second ordination (strategy 2) involved the same four infiltration parameters, but specifically used plots from the burned treatment. More runoff and sediment was associated with the burn shrub coppice plots; in contrast, higher infiltration capacity in the burned interspace. The third ordination (strategy 3) was based on plant canopy cover by species. Discrete taxa of native grasses, forbs, and shrubs were correlated with infiltration, runoff, and sediment loss on burned and unburned sites. On the unburned sites, water repellency and higher runoff was correlated with Sandberg bluegrass (*Poa secunda*), bluebunch wheatgrass (*Pseudoroegneria spicata*), and western aster (*Symphyotrichum ascendens*). Greater infiltration capacity was correlated with increasing cover of Idaho fescue (*Festuca idahoensis*) and mountain big sagebrush. Future analysis will evaluate conditions after the first years growing season and beyond.

Introduction

Fire suppression activities during the past century often increase the severity of wildfires resulting in increased soil erosion and decreased water quality (Pearson and others 2001, 2002). Increased runoff and erosion can lead to loss of soil productivity, flooding, and increased risk to human life and property. Many non-fire related infiltration studies on rangeland have shown that litter and vegetation cover protect the soil and enhance infiltration (Rauzi and others 1968; Blackburn and others 1986). Fire removes this protective covering, reduces soil surface organic matter, and exposes the soil to raindrop impact. After fire, soils can become water-repellent (hydrophobic) although this condition is also common on unburned rangelands (DeBano 1981) and dry soils conditions (Bond and Harris 1964ab; Rutin 1983; Jungerius and de Jong 1989). In the unburned setting, the partially decomposed organic matter from brush species, when intermixed with the soil surface layer, can also produce a water-repellent situation (DeBano and Rice 1973; Pierson and others 2001).

The USDA-ARS Northwest Watershed Research Center (NWRC) has been investigating wildfire interactions with hydrologic processes on steep, coarse textured, sagebrush (*Artemisia*) dominated landscapes in Nevada and Idaho. The sagebrush-steppe is an extensive rangeland shrub type in North America and occupies about 42.5 million ha^2 in the 11 western states. The objectives of these studies are to quantify the impacts of wildfire on infiltration capacity, runoff, erosion, and soil surface characteristics and determine how long fire effects persist. The objective of this paper is to summarize interactions between vegetation, soil, topographic features, hydrologic parameters, and sediment production after a high intensity wildfire.

Study Area

This ongoing study is approximately 24 kilometers southwest of Denio, Nevada, in the Pine Forest Range. The Denio Fire burned in late July 1999 and consumed approximately 34,400 ha. Mean elevation of the research area is 2,050 m, average annual precipitation of the study area is 350-400 mm. Study sites were located on north-facing hillslopes (35 to 40 percent slope). The soil is an Ola bouldery sandy loam which consists of moderately deep soils formed in residuum from granite on mountain sideslopes. The ecological site description is classified as a Granitic slope 14-16" P.Z., mountain big sagebrush/Idaho fescue/bluebunch wheatgrass (USDA-NRCS 1990). Other common subdominant grass species include Columbia needlegrass (*Achnatherum nelsonii*), bottlebrush squirreltail (*Elymus elymoides*), and Sandberg bluegrass. Associated shrubs on the site were common snowberry (*Symphoricarpos albus*) and green rabbitbrush (*Chrysothamnus viscidiflorus*). The major forb species were lodgepole lupine (*Lupinus parviflorus*), nettleleaf giant hyssop (*Agastache urticifolia*), longleaf hawksbeard (*Crepis acuminata*), small bluebells (*Mertensia longiflora*), indian paintbrush (*Castilleja* spp.), alpine lake prairie-dandelion (*Nothocalais alpestris*), Siskiyou Mountain ragwort (*Packera macounii*), arrowleaf balsamroot (*Balsamorhiza sagittata*), rosy pussytoes (*Antennaria rosea*), common yarrow (*Achillea millefolium*), western aster, and low scorpionweed (*Phacelia humilis*).

Methods

Rainfall simulator experiments were conducted in 1999 under antecedent surface soil moisture conditions. The study included two treatment effects: microsites (shrub coppice and interspace) with 20 plots (0.5m²) and 10 plots each on the three burned and unburned areas. A greater number of sample plots were sampled on the burned sites in anticipation of greater variability in response variables compared to the control sites. Four portable oscillating-arm rainfall simulators (specifications described by Meyer and Harmon [1979]) were used to apply rainfall to each runoff plot for 60 minutes. A rainfall rate of 85 mm/hr, equal to the rainfall intensity of a 10-minute thunderstorm with a 10- year return period (Hanson and Pierson 2001), was applied to each runoff plot.

Plot frames were installed immediately after the fire in September 1999 and were left in place for subsequent rainfall simulation treatments. Rainfall was first applied starting 6 weeks following the fire before any natural rainfall events had occurred. All burned and unburned control plots were sampled within 10 days of the start of rainfall simulations. Runoff was routed through a collection tray at the bottom of each plot and collected at one- or two-minute intervals throughout the entire rainfall simulation. Runoff samples were analyzed for runoff volume and sediment concentration by weighing, drying at 105 ºC, and re-weighing each sample. Infiltration capacity for each time interval was calculated as the difference between measured rainfall and runoff.

Prior to the simulation runs, soil samples were collected adjacent to each runoff plot and analyzed for gravimetric soil moisture content. Following rainfall simulation, bulk density using the core method (Blake and Hartge 1986), organic carbon content using the ashing method (Nelson and Sommers 1982), and soil texture using the hydrometer method (Bouyoucos 1962) were determined from soil samples taken immediately adjacent to each plot. Vegetative canopy cover for each plant species, standing dead material, basal vegetative crowns, ground cover of cryptogams, woody and non-woody litter, rock, and bare ground were estimated ocularly to the nearest percent for each plot (Elzinga and others 2000). Some of the rarer species occupy < 1.0 percent canopy cover; therefore, we split the cover classes into finer units (0.05, 0.025, and 0.01 percent). To improve the estimation procedure, each 0.5 m² plot was divided into 4 segments (0.125 m²) and cover values were estimated using a nested frame for calibration, which contained representative areas of 50, 25, 15, 10, 5, 1, 0.05, 0.025, and 0.01 percent. Accuracy of the ocular method was evaluated from random plots by recording 500 points with a point cover frame. Corresponding percent differences between ocular and point cover measurements were not more than ± 2 percent.

The experimental design of this study is given in Pierson and others (2001). In this analysis, indirect gradient analysis using detrended correspondence analysis (DCA) (Hill and Gauch 1980) was used to evaluate plant, soil, site, and hydrology interactions following the wildfire. The following strategies were used: Strategy 1, because all the above ground vegetation including woody stems of shrub species were entirely consumed in the 1999 fire, a comparative ordination (main matrix) using four infiltration parameters was made of both the 1999 burn and unburned sites (n = 90). The infiltration parameters were: minimum infiltration rate (mm/hr)—the lowest average infiltration rate of all sample intervals from the respective rainfall simulation runs; final infiltration rate (mm/hr) is the average infiltration rate of the 58 to 60 min time interval; time to minimum infiltration (min) (equivalent to peak runoff); and cumulative infiltration (mm/hr) calculated as total amount of rainfall applied less cumulative runoff. Secondary matrix environmental variables were correlated with axis loadings from the infiltration data. The environmental variables used appear in Table 1. The axes in DCA are scaled in units of the average standard deviation (SD) of species turnover. A change of 50 percent occurs in about 1 SD. Strategy 2 was the same as 1, except that only burned plots were used (n = 60). The third strategy consisted of a DCA ordination using the 1999 unburned plant species canopy cover data as the main matrix, the secondary matrix data were the environmental factors (n = 30). The false discovery rate (FOR) (Benjamini and Hochberg 1995) was used to test for false positives in the correlation data between axis loadings and plant and environmental variables.

Table 1. Pearson correlations (strategies 1, 2, and 3) with the first two detrended correspondence analysis axes for Denio, Nevada, Mountain big sagebrush study sites (fire year, 1999).

Variables	Strategy 1		Strategy 2		Strategy 3	
	Axis 1 (r)	Axis 2 (r)	Axis 1 (r)	Axis 2 (r)	Axis 1 (r)	Axis 2 (r)
Cumulative infiltration (mm)	-0.67	-0.53	-0.63	-0.55	-0.54	-0.19
Final infiltration rate (mm/hr)	-0.74	-0.45	-0.55	-0.55	-0.55	-0.12
Minimum infiltration (mm/hr)	-0.39	-0.80	-0.83	-0.14	-0.48	-0.31
Runoff/Rain ratio (mm mm)	0.69	0.54	0.66	0.53	0.55	0.18
Cumulative runoff (mm)	0.66	0.54	0.65	0.52	0.54	0.16
Time-to-runoff (min)	-0.04	-0.41	-0.38	0.18	-0.47	-0.34
Time-to-peak runoff (min)	0.47	0.24	0.31	0.40	-0.02	-0.40
Cumulative sediment (kg/ha)	0.15	0.45	0.50	0.31	0.46	0.17
Sediment/Runoff ratio (kg/ha mm)	-0.18	0.19	0.23	0.06	0.23	0.006
Water repellency index	0.83	-0.38	-0.83	0.50	0.66	-0.17
Antecedent moisture 0-2 cm (%)	0.38	-0.10	0.07	0.26	0.01	-0.06
Bulk Density 0-2 cm (g/cm3)	-0.44	0.02	-0.08	-0.09	-0.09	-0.14
Bulk Density 2-4 cm (g/cm3)	-0.55	0.02	-0.19	-0.39	-0.05	-0.007
Grass cover (%)	0.62	-0.08	-0.34	0.20	0.21	0.23
Forb cover (%)	0.13	-0.15	-0.11	0.02	-0.20	-0.21
Shrub cover (%)	0.19	-0.16	-0.24	0.06	-0.32	-0.67
Litter cover (%)	0.54	-0.13	0.16	0.13	0.09	-0.41
Sand 0-2 cm (%)	-0.48	0.10	-0.17	-0.31	0.17	-0.15
Silt 0-2 cm (%)	0.52	-0.08	0.18	0.32	-0.05	0.14
Clay 0-2 cm (%)	-0.12	-0.15	-0.01	0.007	-0.38	0.03
Rock (%)	-0.22	-0.08	-0.16	-0.14	.	.
Slope (%)	0.44	0.19	0.40	0.10	0.10	0.06
Aspect (degrees)	0.27	-0.10	-0.20	-0.44	-0.39	0.21
Microsite (Coppice, Interspace)	0.19	-0.38	-0.60	0.35	0.31	0.69
Microtopography	-0.35	-0.08	-0.20	-0.32	.	.
Treatment (burn, unburn)	0.52	-0.15	.	.	.	.

Results

Strategy 1

Figure 1 is an ordination diagram of 1999 infiltration parameters for the burned and unburned plots. Examination of the burn and unburned treatments shows definitive groupings between burned and unburned treatments along DCA axis 1. The angle and length of the centroid line shows the delineation and degree of correlation of the respective variables. Each line can be related to other variable lines to denote possible environmental gradients (groups of variables). Pearson correlation cutoff values in the ordination diagrams were set at r = 0.50. Table 1 shows correlation coefficients of environmental variables with the first two DCA infiltration axes.

There is a strong infiltration gradient along axis 1 (fig. 1). Final and cumulative infiltration were highly negatively correlated with axis 1. Cumulative infiltration and final infiltration rate decrease toward the right along axis 1; therefore, the burn treatment plots are associated with higher rates for these two variables (table 1). Water repellency as calculated in Pierson and others (2001), cumulative runoff, silt, litter, and runoff-rainfall ratio were positively correlated with axis 1 (table 1). These variables increase in magnitude from left to right. Pierson and others (2001) found that infiltration rate and capacity in water repellent soils after fire were reduced during the early stages of the infiltration curve. In the latter stages of the rainfall simulation, water repellency decreased with time.

The hydrophobic causative agents deteriorated resulting in gradual recovery of infiltration. Bulk density at 2- to 4-cm was negatively correlated with axis 1—higher values in the burned treatment.

An infiltration gradient also appears along axis 2, where minimum infiltration (the lowest average infiltration rate for all sample intervals) and cumulative infiltration are negatively correlated (table 1). In the lower left region, interspace microsite burn plots predominate. Although minimum infiltration is not significant between burned (45.2 mm/hr) and unburned treatments (45.9 mm/hr), it was significant between coppice (37.8 mm/hr) and interspace (53.6 mm/hr) microsites on the burned treatment (Pearson and others 2001). The complementary measurement to cumulative infiltration, cumulative runoff, were positively correlated. Also, the runoff-rainfall ratio was positively correlated with axis 2 (table 1).

Strategy 2

Strategy 2 was included in this paper so that microsites in the burned area could be compared. Figure 2 shows the 1999 burned plots and there were definitive groupings between the interspace and coppice microsites. For an in depth review of the hydrologic data, refer to Pierson and others (2001). Minimum infiltration, cumulative infiltration, final infiltration rate, and water repellency were negatively correlated with axis 1, and cumulative runoff was positive along axis 1. The interspace plots are predominantly on the left side of axis 1 where
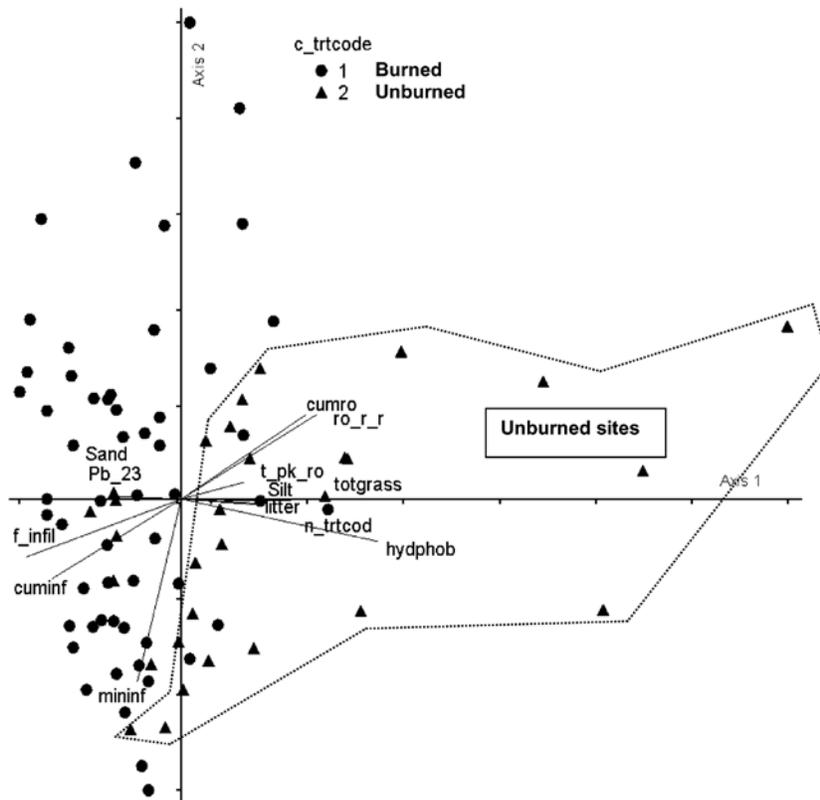
Figure 1. Detrended correspondence analysis of 1999 Denio wildfire hydrology data from all rainfall simulation plots (n=90). Plot points represent an ordination of four infiltration variables [minimum infiltration rate, final infiltration rate, cumulative infiltration rate, and time to minimum infiltration (equivalent to peak runoff)]. Secondary matrix correlations were the remaining variables listed in table 1. Pearson correlation coefficients cutoff values in the figure were set at r = 0.5. The dotted polygon represents the relative grouping of the unburned 1999 sites. The points outside the polygon are the 1999 burned plots. Correlated variables in diagram are: sand, Pb_23=bulk density at 2-4cm, f_infil=final infiltration rate, cuminf=cumulative infiltration, cumro=cumulative runoff, ro_r_r=runoff/rainfall ratio, t_pk_ro=time to peak runoff, silt, litter, totgrass=total grass cover of all species, hydphob=water repellency index, and n_trtcod=treatment (burned and unburned).
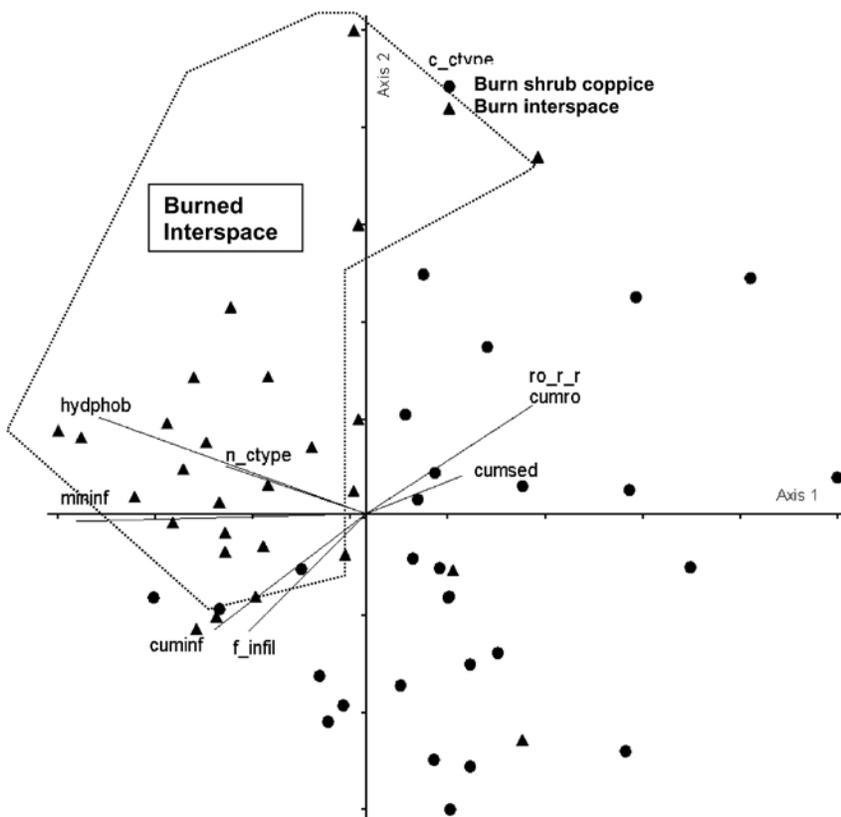
Figure 2. Detrended correspondence analysis of 1999 Denio wildfire hydrology data from rainfall simulation burned plots (n=60). Plot points represent an ordination of four infiltration variables [minimum infiltration rate, final infiltration rate, cumulative infiltration rate, and time to minimum infiltration (equivalent to peak runoff)]. Secondary matrix correlations were the variables listed in table 1. Pearson correlation coefficients cutoff values in the figure were set at r = 0.5. The dotted polygon represents the relative grouping of the burned interspace 1999 plots. The points outside the polygon are the 1999 burned shrub coppice plots. Correlated variables in diagram are: hydphob=water repellency index, mininf=minimum infiltration rate, cuminf=cumulative infiltration, f_infil=final infiltration rate, n_ctype=microsite cover type (interspace, coppice), ro_r_r=runoff/rainfall ratio, cumro=cumulative runoff, and cumsed=cumulative sediment.
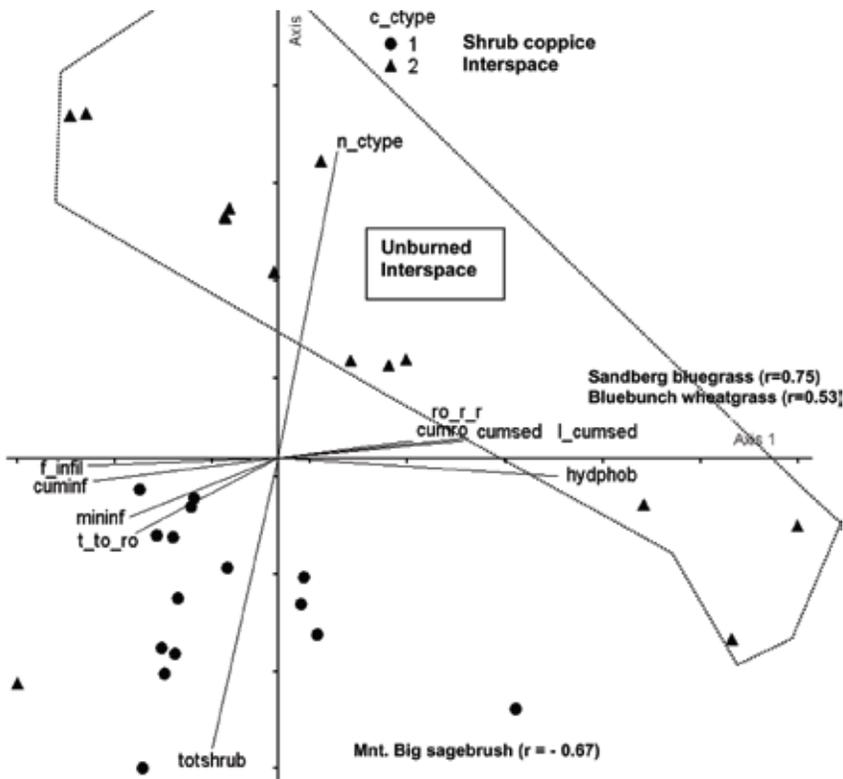
Figure 3. Detrended correspondence analysis of 1999 Denio wildfire hydrology data from rainfall simulation unburned plots (n=30). Plot points represent an ordination of plant canopy cover for all species. Secondary matrix correlations were the variables listed in table 1. Pearson correlation coefficients cutoff values in the figure were set at r = 0.5. The dotted polygon represents the relative grouping of the unburned interspace 1999 plots. The points outside the polygon are the 1999 unburned shrub coppice plots. Correlated variables in diagram are f_infil=final infiltration rate, cuminf=cumulative infiltration, mininf=minimum infiltration rate, t_to_ro=time-to-runoff, totshrub=total shrub canopy cover, n_ctype=microsite cover type (interspace, coppice), ro_r_r=runoff/rainfall ratio, cumro=cumulative runoff, cumsed=cumulative sediment, l_cumsed=log of cumulative sediment, and hydphob=water repellency index. Correlated plant species appear in the respective ordination quadrants.

average final infiltration, cumulative infiltration, minimum infiltration, and water repellency were higher compared to the shrub coppice to the right on axis 1. As Pierson and others (2001) mentioned, there was more fuel on the shrub coppice microsites which may have resulted in higher burn temperatures and a greater tendency for water repellent conditions. Fire vaporizes some organic compounds on the soil surface and distills the rest downward, concentrating the hydrophobic substances in the upper soil surface. On the right side of axis 1 where the coppice plots are grouped, cumulative sediment yield was higher coppice = 410 kg/ha; interspace = 210 kg/ha (fig. 2). The runoff-rainfall ratio was also higher for the burned shrub coppice area (0.37 mm mm) compared to the burned interspace (0.30 mm mm) (fig. 2).

Strategy 3

Figure 3 is an ordination of plant canopy cover data for all species in the unburned area. In figure 3, the unburned coppice and interspace microsites are definitively separated. The microsite groupings are unique with respect to plant species composition. Near plots have more similar plant species composition, far plots are more dissimilar. Along axis 1, final infiltration and cumulative infiltration are associated with the shrub coppice microsites. In contrast, cumulative runoff, runoff-rainfall ratio, water repellency, and cumulative sediment are higher in the unburned interspace.

In Pierson and others (2001), final infiltration rates were about equal between the burned (55.5 mm/hr) and the unburned coppice (55.9 mm/hr) plots. After an intense wildfire, we expected to see a difference in infiltration rates between the coppice microsites; however, infiltration between burned and unburned coppice areas immediately after the fire was about the same. We propose that the litter buildup in the unburned treatment area was responsible. On the unburned plots, litter averaged 5 cm deep and averaged 7,275 kg/ha with a high value of 11,605 kg/ha. The litter, sagebrush duff, and grass on shrub coppice and senescent grass in the interspace apparently have water repellent properties. We observed this during the rainfall simulation experiments. In contrast to the coppice areas, final infiltration rate in the burned interspace (60.0 mm/hr) was significantly greater compared to the unburned interspace (40.4 mm/hr).

In figure 3, Sandberg bluegrass and bluebunch wheatgrass were positively correlated with axis 1 (> canopy cover), the zone of unburned interspace plots. Idaho fescue was negatively correlated with axis 1—where the unburned shrub coppice plots have higher Idaho fescue and Columbia needlegrass canopy cover. Regression analyses of the unburned data showed:

Infiltration = f (+ Idaho fescue, + Columbia needlegrass, + mountain big sagebrush),

Runoff = f (+ Sandberg bluegrass, + bluebunch wheatgrass + western aster),

Cumulative sediment = f (+ Sandberg bluegrass, + western aster),

where *f* = function of the following independent variables, + sign indicates positive association.

Spaeth and others (1996, 2003) proposed that plant species appear to have an impact on rangeland hydrology. Therefore,

we hypothesize that plant species (considering importance values such as cover, biomass, and root biomass) can affect hydrology.

Discussion

In Pierson and others (2001), we showed that wildfire can have a significant hydrologic impact on the hydrology of sagebrush dominated rangelands. In Pierson and others (2001) we hypothesized that during the burn year, average infiltration rates would be reduced on the burned compared to the unburned treatment because of soil water repellency caused by the hot fire. This hypothesis was rejected because rainfall simulation experiments shortly after the fire did not result in a significant effect on average infiltration between the burn and unburned treatments.

A second hypothesis was tested: infiltration rates will be different between microsites for burned and unburned treatments (based on previous work by Blackburn 1975, Pierson and others 1994). Infiltration rates were reduced on burned shrub coppices compared to burned interspace. Burned shrub coppice microsites were associated with very uniform fire induced water repellency with an average infiltration rate reduction of 28 percent. On unburned plots, infiltration rates were greater on the shrub coppice areas compared to interspace areas. Comparisons between burned and unburned treatments showed that infiltration rates were about the same on coppice microsites, but different between interspace areas. Infiltration was higher, and runoff lower, on the burned interspace compared to the unburned interspace. Pierson and others (2001) attributed this unexpected result to the dense mat of senescent grass (litter) on the soil surface. The water repellent litter in the interspace area intercepted the rainfall and initiated runoff before the water reached the mineral soil surface.

In this paper, we examined possible relationships between individual species composition and hydrology. In mountain big sagebrush vegetation, plant composition, and soil physical properties are different in microsite areas (shrub coppice, shrub dripline, and varying distances along the interspace). Idaho fescue, lupine, mountain big sagebrush, and snowberry are more prevalent in the coppice areas; whereas, Sandberg bluegrass, bluebunch wheatgrass, rosy pussytoes, common yarrow, and western aster occur mostly in the interspace areas. The presence or absence and magnitude of canopy cover of certain plant species seems to be associated with infiltration capacity, runoff, and sediment loss. This preliminary study showed certain plant species were associated with higher and lower infiltration and runoff. In figure 3, textural differences, antecedent moisture, bulk density, total grass cover, and total forb cover were not correlated with the infiltration gradient (unburned coppice to unburned interspace). However, Idaho fescue and Columbia needlegrass canopy cover were correlated with higher infiltration; whereas, Sandberg bluegrass and bluebunch wheatgrass were associated with higher runoff.

Future analysis will incorporate several more years of rainfall simulation experiments at Denio, Nevada to determine the impact of these plant species on hydrology in high elevation mountain big sagebrush vegetation. In addition to the Denio sites, the NWRC is conducting similar rainfall simulation experiments at sagebrush sites at Reynolds Creek Experimental Watershed in southwest Idaho.

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