

Shrub Mounds Enhance Water Flow in a Shrub-Steppe Community in Southwestern Idaho, U.S.A.

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Abstract: In the Western United States, substantial areas of shrub-steppe have been replaced by annual exotic grasses during the past century. These structural changes have been accompanied by functional changes in the landscape in relation to the ability of the landscape to capture essential resources such as water and sediments. Surface waterflow was measured in three contrasting shrub-steppe communities (sagebrush, winterfat, and rabbitbrush) on mound and interspace surfaces using disc permeameters. Waterflow was substantially greater (2 to 6 times) under shrubs compared with the shrub-free, microphytic-dominated interspaces. The ratio of sorptivity under ponding to sorptivity under tension, which is a useful index of the macropore (pores > 0.75 mm in diameter) status of the soil, demonstrated that mounds were characterized by a significantly greater amount of macropores compared with interspaces. The dense cover of the moss *Tortula ruralis*, which grows below *Artemisia* canopies, intercepted approximately 14 L of water m⁻² and enhanced the infiltration capacity of shrub mound soils. The results reinforce the notion that these shrub-steppe communities are partitioned into moisture-rich mounds separated from moisture-deprived interspaces that are critical for the transfer of water to the shrub mounds. Disturbance of the interspaces ultimately leads to a reduction in water reaching the mounds and a decline in shrubland function.

Introduction

Since the late nineteenth and early twentieth centuries, extensive and uncontrolled livestock grazing has resulted in substantial changes to the composition and structure of many native shrub-steppe communities. The combined impact of grazing and invasion of annual Eurasian weeds (Mack 1981), primarily cheatgrass (*Bromus tectorum* L.) and medusahead (*Taeniatherum caput-medusae* ssp. *asperum* L.), have increased the risk of wildfire in shrub communities (Wambolt and others 2001). Consequently,

increased frequency of wildfire has resulted in conversion of substantial areas of *Artemisia* shrub-steppe to annual grasslands, which in turn burn at intervals of less than 10 years (Whisenant 1990). This increasing cycle of fire, conversion to annual grasslands, and more fire has increased unabated, and now large areas of grassland exist in former shrub-steppe communities.

The dramatic change from shrublands to annual grasslands has resulted in substantial changes in landscape function at both local and regional scales. Changes in landscape structure have resulted in major impacts on biodiversity, including loss of overstory and understory flora, declines in many faunal taxa, and invasion of exotic species (Wambolt 2001, 2002; West 1993). Spatial heterogeneity in many shrub-steppe communities worldwide is characterized by a matrix of microphytic crust-dominated soils (the interspaces) on which are superimposed soil mounds colonized by perennial shrubs (shrub mounds). The microphytic crusts of the interspaces comprise cyanobacteria, bacteria, algae, mosses, and lichens (Hilty and others 2004; West 1990). Cyanobacterial polysaccharides bind together the surface of the interspace soils, giving it a tight microstructure that generally repels water (Eldridge and others 2000). In contrast, the surface soil of the shrub mound lacks the microphytic crust and is covered with loose soil particles. On functional shrub-steppe landscapes, these contrasting surfaces result in the concentration of water and nutrients within the nutrient-enriched shrub patches at the expense of the nutrient- and water-deprived interspaces (Blark and Small 2003; Schlesinger and others 1990; Thiery and others 1995; Tongway and Ludwig 1994). This patchiness exists at a range of spatial scales from whole catchments and subcatchments to individual plants.

Efficient, sustainable production of arid shrublands is dependent upon the movement of water, sediments, seed, and soil from the interspace to the shrub mounds. When these shrublands become degraded, resources are no longer trapped within the shrub mounds, and the landscape becomes dysfunctional (Ludwig and Tongway 1995). Healthy soils within shrub mounds are characterized by a high degree of macroporosity, that is, a large number of pores, generally biological in nature, greater than about 0.75 mm in diameter. These pores are important for capturing excess water generated from the interspaces. These macropores or biopores are destroyed by trampling, disturbance, and cultivation. Waterflow through soils over small spatial scales can

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be quantified using disc permeameters (White 1988). Using the permeameters, a measure of the ratio of waterflow under ponding to flow under tension can be obtained. This ratio gives an indication of the relative health of the soil. Other indicators of soil health include the relative differences in infiltration between mound and interspace soils, as well as the total infiltration capacity of the soil.

The aims of the research reported here are threefold. Firstly, we wished to examine relative differences in infiltration on three soil types supporting three different shrub-steppe communities common on the Snake River Plain. Secondly, we wished to test whether there were significant differences in infiltration between shrub mounds and adjoining interspaces in order to learn more about the consequences of shrub removal on the surface movement of water. Thirdly, we were interested in examining the relative effect of mosses growing below the shrub canopy on the interception, storage, and infiltration of water. We addressed these questions by applying water to shrub mound and intershrub (interspaces) areas using disc permeameters.

Methodology

Study Sites

Three sites were selected for detailed infiltration measurements: Bowns Creek (116°18'00"W, 43°12'00"N) approximately 48 km southeast of Boise, Cindercone Butte (115°56'30"W, 43°20'30"N) approximately 56 km southeast of Boise, and Kuna Butte in the Birds of Prey Reserve (116°25'32"N, 43°25'59"W) approximately 20 km southwest of Boise, ID. These sites were chosen because they contained typical examples of three different types of shrub morphologies on different soils (loam, sand, and silt, respectively) at sites close to Boise. Further, the sites were not adversely impacted by encroachment of exotic annual grasses such as cheatgrass and medusahead. All sites were on level (less than 1 percent) slopes. A description of the biotic and abiotic features of the sites is given in table 1.

Waterflow

The soil body consists of a matrix of soil, minerals, air, and organic matter through which a network of pores of various size and shape pass. Large soil pores (macropores), generally greater than 0.75 to 1.00 mm in diameter, are important in the transfer of water and nutrients through the soil (Bouma

1991) and are generally biological in origin. Macropores are formed by plant roots and soil fauna (Oades 1993), and as pore size increases, capillary tension declines and waterflow increases. Smaller pores (micropores or matrix pores) are also present between individual mineral grains and between soil particles, but are not formed by soil biota.

The early phase of waterflow (2 to 10 minutes after water is applied) is termed sorptivity, during which water enters the soil in response to potential gradients of water potential (influenced by soil dryness and pore structure), and gravitational potential (pore size, distribution and continuity; White 1988). The sorptivity phase is largely governed by the capillary properties of the soil, particularly when it is dry. As the soil wets up, gravitational forces become more important (White 1988). The second phase of infiltration is known as the steady-state phase. In uniform soils, a time is reached where the flow rate from the source (in our case the disc permeameter) stabilizes over time. This steady-state flow rate or steady-state infiltration is governed by capillarity, gravity, the area of the disc permeameter in contact with the soil, and the pressure at which the water is supplied to the soil surface (CSIRO 1988).

Both sorptivity ($\text{mm h}^{-0.5}$) and steady-state infiltration (mm h^{-1}) were measured with disc permeameters at supply potentials of -40 mm (tension) and $+10$ mm (ponded) (Perroux and White 1988). When a negative pressure or tension is applied to the soil using the disc permeameter, water is prevented from entering macropores, and water only flows through matrix pores. However, when infiltration is measured with a positive pressure, water flows through both macropores and matrix pores. As these two tensions measure the contribution by different pore sizes, the ratio of sorptivity at $+10$ mm to flow at -40 mm is a useful index of the relative contribution of macropores to total waterflow. This is an extremely informative measure, as macropores are indicative of healthy, highly conductive soils, and a loss of ecosystem function in terms of waterflow can be attributed in a large part to a loss of this macroporosity.

At each of the three sites, five replicate measurements of waterflow were made at two microsites (shrub mound and interspace). The ponded permeameter was placed on a steel ring of 220 mm internal diameter, which was gently pressed into the soil to a depth of about 7 to 10 mm, and sealed with moistened soil along the outside edge to prevent leakage of water. Both permeameters were placed alongside each other and run for approximately 30 minutes, by which time steady-state had been achieved. At each supply potential, sorptivity

Table 1—Description of three sites.

| Description | Bowns Creek | Cindercone Butte | Kuna Butte |
|------------------------------------|--|---|--|
| Dominant vegetation community | Wyoming big sagebrush (<i>Artemisia tridentata</i> subsp. <i>wyomingensis</i>) | Rabbitbrush (<i>Chrysothamnus nauseosus</i>) | Winterfat (<i>Krascheninnikovia lanata</i>) with scattered Wyoming big sagebrush |
| Soil type | Loamy to clay loam Xerollic Durargids and Xerollic Haplargids | Loamy fine sand overlying sandy loams; Xerollic Camborthids | Silts and silty loams; Durinodic Haplocalcid |
| Shrub density (ha^{-1}) | 7,140 | 81,600 | 30,200 |
| Grazing status | Ungrazed | Intermittently grazed | Ungrazed enclosure |

was calculated according to the method of Cook and Broeren (1994), and steady-state infiltration according to White (1988).

Impact of Mosses on Infiltration

Tortula ruralis, the dominant tall moss in sagebrush steppe, is common in sheltered microsites beneath shrub canopies (Rosentreter 1994) where it forms extensive mats on the soil surface (Hilty and others 2003). In order to measure the impact of this thick cover of moss on waterflow, infiltration was remeasured, at the Bowns Creek site only, at each of the exact same mound locations after all moss had been carefully removed from the soil surface. We carefully removed all of the moss without damaging the soil, then allowed 5 days for the soil to equilibrate to its preinfiltration level of soil moisture. Ponded infiltration was then remeasured over 25 minutes. The amount of infiltration into the soil is the difference between the volume of water leaving the permeameter and the volume of water intercepted and stored by the moss. We removed the moss samples from below the permeameters, transported them back to the laboratory, and saturated them with water in order to calculate the amount of water intercepted by mosses. Excess water was allowed to drip off over a period of 20 minutes before the samples were weighed.

Soil Surface Morphology

At Bowns Creek, Cindercone Butte, and Kuna Butte we measured the percentage cover of each of five surface morphology types (Hilty and others 2003) adjacent to each of the five infiltration locations along two 5-m transects using the line-intercept method (Canfield 1941). A detailed description of the five soil surface morphological types (coppice, coppice bench, microplain, playette, disturbed), which have been adapted from Eckert and others (1978), is given in Hilty and others (2003).

Data Analyses

General Linear Models were used to test for differences in sorptivity, steady-state infiltration, and soil surface morphology between the three sites and between the two microsites and their interactions, after checking for homogeneity of variance (Levene's test) using Minitab (1997). We used a split-plot model with sites fixed and locations within a site random. This enabled us to account for the variability between the mound and nonmound microsites among the five replicate locations at each site.

Results

Soil Surface Morphology

Overall, coppice, coppice bench, and microplain surface morphologies accounted for about 90 percent of the surface of the soils across all sites. Although there were few differences in the proportion of most surface cover types between the three sites, there was a significantly greater cover of coppice bench at Bowns Creek compared with the other sites ($F_{4,48} = 17.64$, $P < 0.001$; fig. 1).

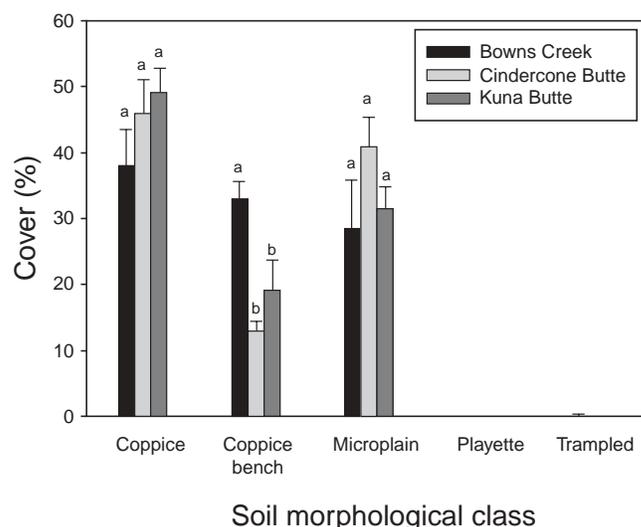


Figure 1—Cover of the five morphological classes at the three sites. Different letters within a class indicate a significant difference in that class between the three vegetation communities.

Infiltration

There were no significant differences in sorptivity or steady-state infiltration under tension between the three sites or between mound and interspace microsites (table 2; fig. 2). Under ponded conditions, both sorptivity and steady-state infiltration were significantly greater at Cindercone Butte compared with the other sites ($F_{2,12} = 6.9$ and 20.6 , respectively) (table 2; fig. 2). Both sorptivity and steady-state infiltration were significantly greater in soil below the shrubs compared with in the interspaces ($F_{1,12} = 28.1$ and 22.7 , respectively; $P < 0.001$). The greatest differences between shrub and interspace soils occurred at Bowns Creek where steady-state infiltration under the shrubs was more than $6.6 (\pm 1.1 \text{ SEM})$ times that in the interspaces. Infiltration through the mounds at Cindercone Butte and Kuna Butte was about twice that in the interspaces (fig. 2).

As indicated above, the ratio of sorptivity under ponding to sorptivity under tension is a useful index of the macropore status of the soil (White 1988). This ratio was significantly greater on the shrub mounds (range 8.0 at Kuna Butte to 20.0 at Cindercone Butte) compared with the interspaces (range 2.0 to 8.1; $F_{1,12} = 16.8$, $P = 0.01$), indicating the abundance of macropores below the shrub mounds.

The rate of infiltration was generally more variable in the presence of the moss *Tortula ruralis*. At about 17 minutes after commencement of water application, infiltration in the presence of moss cover significantly exceeded infiltration with moss removed (fig. 3). Over the surface area of the permeameter (220 cm^2), *Tortula ruralis* intercepted a substantial amount of water (0.5 L), and by the cessation of infiltration measurements, total infiltration of water in the presence of moss (5.15 L) was 42 percent greater than that without moss (2.99 L).

Table 2—Breakdown of site and microsite effects on sorptivity and steady-state infiltration under tension and ponding, and the macropore status of soils.

| Parameter | Site effects ^a | | Microsite effects ^b | |
|---|---------------------------|----------|--------------------------------|-----------|
| | Trend | P | Trend | P |
| Sorptivity under tension | B = K = C | P = 0.19 | M = I | P = 0.110 |
| Sorptivity under ponding | C > (B = K) | P < 0.01 | M > I | P < 0.001 |
| Steady-state infiltration under tension | B = K = C | P = 0.79 | M = I | P = 0.220 |
| Steady-state infiltration under ponding | C > (B = K) | P < 0.01 | M > I | P < 0.001 |
| Macropore status ^c | C > (B = K) | P = 0.04 | M > I | P < 0.001 |

^aB = Bowns Creek, K = Kuna Butte, C = Cindercone Butte.

^bM = shrub mound, I = interspace.

^cRatio of sorptivity under ponding (+10 mm) to sorptivity under tension (-40 mm).

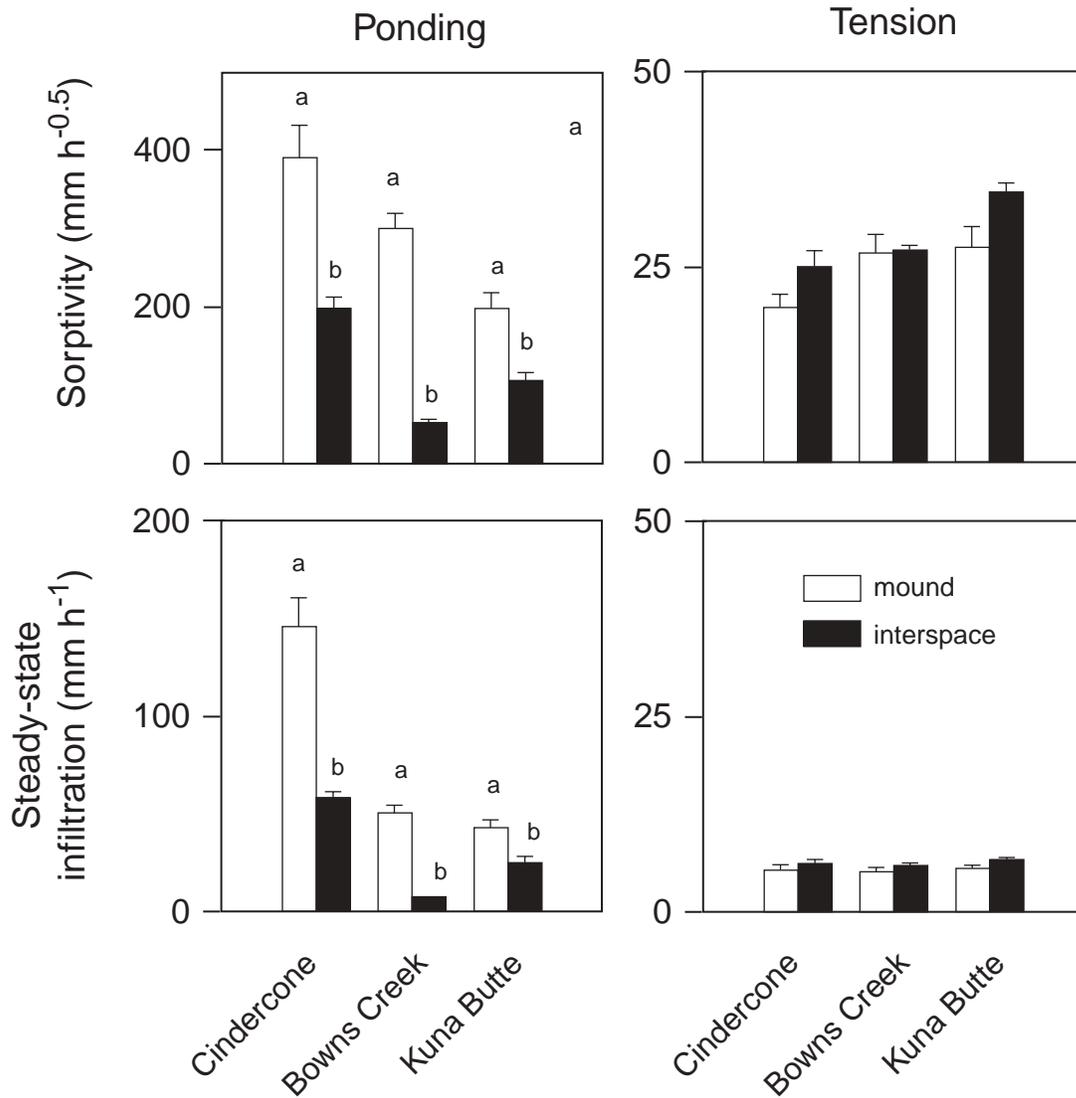


Figure 2—Mean (\pm standard error of the mean) sorptivity and steady-state infiltration under ponding and tension on mound and interspace microsites at the three sites. Different letters at a site indicate a significant difference at $P < 0.05$.

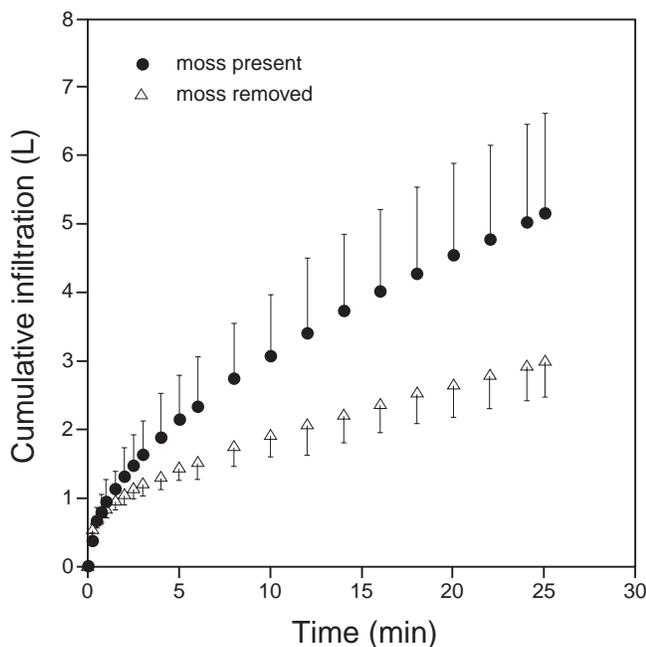


Figure 3—Mean (\pm standard error of the mean) cumulative infiltration (L) on five mounds with *Tortula ruralis* intact and later removed. A significant difference in cumulative infiltration occurs after about 17 minutes.

Discussion

In our study, infiltration under the shrubs was two to six times greater than infiltration in the interspaces (fig. 2). We attribute the major difference in infiltration to structural differences in the two microsites, and in particular, differences in the macroporosity status of each microsite. Soil surface morphology was relatively similar between sites (fig. 1), and higher sorptivity and infiltration at the Cindercone site is attributed to the coarser (sandier) texture at that site (table 1).

Increased infiltration under shrubs has been demonstrated in a range of desert and semidesert environments. Scholte (1989) showed that the rate of infiltration under shrubs was 20 times greater than adjacent nonshrub surfaces, while greater flow under woody plants can be attributed to differences in macropores (Devitt and Smith 2002). Greene (1992) demonstrated tenfold greater infiltration rates in mulga (*Acacia aneura*) groves compared with adjacent sparsely populated runoff slopes. Our results emphasize the importance of shrubs for enhancing infiltration, reinforcing the notion that in these environments shrubs act as “fertile islands” (Parsons and others 2003).

A number of factors contribute to the different hydrologic response near shrubs (Dunkerley 2000). Direct plant effects include absorption of raindrop energy by the plant canopy (Whitford and others 1997), which often changes soil water levels and influences the microclimate of the surface, a greater abundance of roots near the surface creating macropores that facilitate waterflow (Beven and Germann 1982), and changes in soil litter cover and plant cover in the

vicinity of shrubs that influence the retention and absorption of water (Geedes and Dunkerley 1999). Shrubs can also influence waterflow indirectly by altering adjacent physical and chemical properties of the soil, making the soil more conducive to soil invertebrates (Dunkerley 2000).

Despite the marked differences in sorptivity and steady-state infiltration under ponding, we failed to find any differences under tension when flow was restricted to pores between individual soil particles (matrix pores). There were no site effects nor any differences between shrub mounds and interspaces (fig. 2). This indicates to us that the matrix pore capacity of these soils is very similar, and that the soils have a relatively similar inherent ability to conduct water, which, in the absence of macropores, was quite low (fig. 2). Thus, infiltration rates in these soils are largely driven by macropores, and the greater infiltration under shrubs compared with the interspaces is due to the higher density of biologically derived macropores, probably plant root and faunal holes.

The movement of surface water is the critical process in semiarid and arid landscapes where essential resources are patchily distributed in the landscape. Some zones (source or runoff zones) respond rapidly to rainfall by shedding runoff water, directing it to adjoining patches which absorb water (sink zones). The result is a series of fertile patches or “islands” with enhanced soil moisture at levels greater than that which they would normally receive through natural rainfall (Yair 1994). In healthy landscapes these sinks cover about 30 percent of the surface (Tongway 1990). The marked differences in infiltration capacity between the shrub mounds and interspaces reinforces our view that these shrublands are strongly patterned into two distinct geomorphic zones: (1) a water shedding interspace and (2) a water accreting shrub mound (Ludwig and Tongway 1995).

On the sparsely vegetated interspaces, cryptogamic crusts create a matrix of small runoff zones (Hilty and others 2003) separated by the tussocks of small grasses, principally *Poa secunda*, which function as localized sites for water accumulation. These *Poa* microhummocks, while contributing to patchiness at small spatial scales, are thought to result from previous periods of degradation, and may be a sign of a recovering landscape (M. Pellant 2000, personal communication). During very small rainfall events, the *Poa* microhummocks hold most of the runoff water that is generated off the relatively hydrophobic (water repelling) cryptogamic crusts. However, larger rainfall and intense storms are likely to generate runoff, which is captured in the shrub mounds (Wainwright and others 1999) that have the capacity to absorb substantial volumes of runoff. Our infiltration measurements indicate that the shrub mounds are capable of soaking up substantial quantities of surface runoff, functioning as “ecological straws” in high rainfall years.

Some of this water retention in our study was due to the extensive cover of the moss *Tortula ruralis* below the shrubs (fig. 3). *Tortula ruralis* is generally restricted to shrub canopy and grass microsites (Rosentreter 1984) where it forms extensive mats on the soil surface. *Tortula ruralis* is well adapted to prolonged desiccation (Longton 1992) and quickly rehydrates after rainfall. Our study showed that *Tortula* can store about 0.5 liters of water over an area of 0.038 m^2 , or $14.2 \text{ liters m}^{-2}$. The destruction of moss cover

after fire (Hilty and others 2004) has the capacity therefore to reduce substantial amounts of water, which may be important for invertebrates resident within shrub-steppe ecosystems.

Shrub patches receiving enhanced water and nutrients would be expected to have higher levels of soil nutrients, particularly organic carbon and nitrogen, and greater populations of soil biota, and would be expected to be preferred sites for germination and survival of vascular plants compared with the interspaces. The *Chrysothamnus* site at Cindercone showed evidence of invasion by annual grasses, particularly cheatgrass, and the shrub mounds were poorly developed in comparison with the finer textured soils at Kuna Butte and Bowns Creek (table 1). Nevertheless, landscape patchiness appears to be governed by the distribution of shrubs, particularly *Chrysothamnus* and *Artemisia* spp., which show evidence of deep deposition of litter under the canopy.

Disturbance of the well-developed microphytic crust in the interspaces, particularly at Bowns Creek and Kuna Butte, is likely to lead to increased infiltration in the interspaces, invasion of the interspaces by annual species such as cheatgrass, and reduced redistribution of runoff to the shrub mounds. The breakdown in patchiness means that annual rainfall alone (in the absence of runoff) may be insufficient to sustain the growth of perennial shrubs. Reduced infiltration through the mounds is likely to lead to a change in the composition of vascular plants to one dominated by weedy ephemerals. In the short-term, death of the perennial shrubs will result in reduced infiltration rates, erosion around the mound base, reduced trapping of wind- and water-borne sediments (dust), and eventually partial breakdown of the mounds (Offer and others 1998). The long-term effect of removal of the water-shedding crust is a disintegration of the mounds, and a general decline in rangelands productivity and condition (Eldridge and others 2000).

Conclusions

The results confirm the importance of landscape patchiness in controlling the distribution of water in shrub-steppe ecosystems. Shrub mounds represent a stable, healthy landscape, and their enhanced water status results in higher diversity and productivity. Activities that disturb the soil surface in the interspace have the capacity to reduce runoff to the shrub mounds and therefore reduce cover of the shrubs. Long-term management of desert shrublands should aim to maintain the integrity of both the mound and interspace, ensuring the efficient functioning of shrub and shrubland biota.

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