Hydraulic Conductivity in a Piñon-Juniper Woodland: Influence of Vegetation

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ABSTRACT

In semiarid environments, vegetation affects surface runoff either by altering surface characteristics (e.g., surface roughness, litter absorption) or subsurface characteristics (e.g., hydraulic conductivity). Previous observations of runoff within a piñon-juniper [*Pinus edulis* Englem. and *Juniperus monosperma* (Englem.) Sarg.] woodland led us to hypothesize that hydraulic conductivity differs between vegetation types. Using ponded and tension infiltrometers, we measured saturated (K_s) and unsaturated [$K(h)$] hydraulic conductivity at three levels of a nested hierarchy: the *patch* (canopy and intercanopy), the *unit* (juniper canopy, piñon canopy, vegetated intercanopy, and bare intercanopy), and the *intercanopy locus* (grass, biological soil crust, bare spot). Differences were smaller than expected and generally not significant. Canopy and intercanopy K_s values were comparable with the exception of a small number of exceedingly high readings under the juniper canopy—a difference we attribute to higher surface macroporosity beneath juniper canopies. The unsaturated hydraulic conductivity, $K(h)$, values were higher for canopy soils than for intercanopy soils, although differences were small. At the unit level, the only significant differences were for $K(h)$ between juniper or piñon canopies vs. bare interspaces. Median K values for vegetated intercanopy areas were intermediate between but not significantly different from those for canopies and bare areas. There were no significant differences between grass, biological soil crust, and bare spots within the herbaceous intercanopy area. Overall, the observed differences in K between canopy and intercanopy patches do not account for differences in runoff observed previously.

In semiarid landscapes, there is generally an inverse relationship between vegetation cover and overland flow. In other words, all other factors being equal, the more vegetation, the less overland flow. This may occur either as a result of enhanced soil infiltrability, for which hydraulic conductivity (K) is a direct indicator, or modified surface characteristics (e.g., a change in surface roughness or surface storage), such that water has greater opportunity to infiltrate into the soil. In this paper we examine the relationship between one of these factors, soil infiltrability, and vegetation cover in a piñon-juniper community in New Mexico.

Soil infiltrability is closely linked to vegetation cover. The literature is replete with examples of the positive relationship between vegetation cover and soil infiltrability—showing, in particular, that the infiltrability of soils under shrub canopies is generally higher than that of intercanopy soils. Significantly higher infiltrability has been documented for shrub canopy soils in sagebrush rangelands (Blackburn, 1975; Johnson and Gordon, 1988; Pierson et al., 1994; Seyfried, 1991), creosote shrublands (Elkins et al., 1986; Lyford and Qashu, 1969; Wainwright et al., 2000), mesquite rangelands (Wood and Blackburn, 1981), and piñon-juniper rangelands in the USA (Roundy et al., 1978). Similar findings have been reported from other parts of the world. Examples are Australia, where studies were performed in both mulga woodlands (Greene, 1992) and arid shrublands (Dunkerley, 2000a); Niger, in tiger bush (Bromley et al., 1997); and Spain, in semiarid shrublands (Cerda et al., 1998). In other studies, differences in infiltrability have been found within the intercanopy, between areas exhibiting differing degrees of herbaceous cover (Wilcox et al., 1988). Similarly, Wood and Blackburn (1981) found higher infiltration rates for mid-grass than for short-grass areas. And in Spain, Cerda (1997) reported that infiltration rates under the grass species *Stipa tenacissima* were almost double those for adjacent bare ground.

Enhanced infiltrability under vegetation canopies may be due to a number of factors, including textural differences resulting from rain splash or trapping of eolian sands by vegetation (Parsons et al., 1992); higher organic-matter content of the soil under vegetation; protection of the soil surface by leaf litter; enhanced aggregation; and a more developed network of macropores (Dunkerley, 2000a). Intercanopy soils often have low infiltrability that could be a result of the relatively harsher microclimate (Breshears et al., 1998), comparatively small inputs of organic matter, and the development of an erosion pavement or soil crust layer (Blackburn et al., 1975). Within the intercanopy zone itself, soil infiltrability has been observed to vary with differences in surface cover. The biological soil crusts that are common in arid and semiarid landscapes modify soil hydrology and stability in these regions (Belnap and Lange, 2001). The relative effect of these modifications has been demonstrated to be strongly influenced by soil texture: studies show that biological soil crusts reduce the infiltrability of very sandy soils, whereas they enhance or have little effect on the infiltrability of more fine-textured soils (Warren, 2001).

On the basis of the extensive literature establishing the strong linkage between vegetation cover and numerous hydrologic characteristics—including infiltration, runoff, and erosion—we propose that in semiarid landscapes vegetation cover can serve as the criterion for the identification of "hydrologic functional units" (Wilcox and Breshears, 1995). This may be a useful approach for dealing with the strong scale-dependent relationship for runoff in semiarid landscapes (Seyfried and Wilcox, 1995; Wilcox et al., 2003). At larger scales, for example, runoff per unit area dramatically decreases with increas-

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Abbreviations: K_s, saturated hydraulic conductivity; $K(h)$, unsaturated hydraulic conductivity.

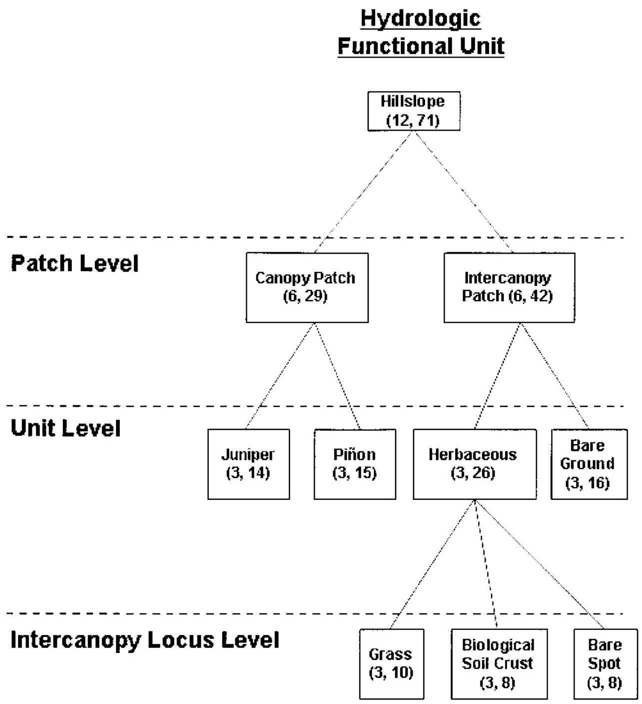

Fig. 1. The nested hierarchy for the hydrologic functional units in piñon-juniper ecosystems. The numbers in parentheses indicate the number of sites and locations sampled within each category.

ing scale as a result of stream-channel-transmission losses (Goodrich et al., 1997). At the hillslope scale, storage as a function of vegetation cover and microtopography also diminishes unit-area runoff as scale of observation increases (Wilcox et al., 2003).

Borrowing from Reynolds and Wu (1999), we define a hydrologic functional unit as a discrete and scale-dependent landscape unit having hydrologic characteristics that are internally homogenous and quantitatively and qualitatively different from those of its immediate surroundings. For piñon-juniper woodlands, we propose a hierarchy of levels nested according to spatial scale. Within each level, hydrologic functional units are defined on the basis of vegetation and cover characteristics.

For our study, we defined hydrologic functional units within the hillslope level. The first hierarchical subdivision is the *patch* level, which comprises two hydrologic functional units: the canopy patch and the intercanopy patch. Next in scale is the *unit* level, which comprises four hydrologic functional units: two in the canopy category (juniper canopy and piñon canopy) and two in the intercanopy category (herbaceous intercanopy and bare ground intercanopy). The herbaceous intercanopy can be further subdivided into three hydrologic functional units at the intercanopy locus level: grass, biological soil crust, and bare spot (Fig. 1).

In previous papers (Reid et al., 1999; Wilcox, 1994), we reported on work at the Mesita del Buey study site (elevation 2140 m, 34.30° N lat., 106.27° W long.), where we examined runoff and erosion characteristics at the patch level and at the intercanopy unit level. We found that both runoff and erosion were much higher in intercanopy patches than in canopy patches; and that within the intercanopy patches, runoff and especially erosion were higher for the bare than for the herbaceous intercanopy units. Davenport et al. (1996), working at the same location, found little relationship between soil properties and vegetation cover.

In this paper, we examine the relationship between soil hydraulic conductivity (K) and vegetation characteristics at the same site, Mesita del Buey, by comparing the hydraulic conductivities (saturated [K_s] and unsaturated [$K(h)$]) of the hydrologic functional units at the various hierarchical levels (see Fig.1). This study was designed to test the hypothesis that K in piñon-juniper woodlands varies in consistent and predictable ways among the hydrologic functional units and that differences in K, particularly K_s, account for differences in runoff we observed in the earlier study (Reid et al., 1999). Specifically, we hypothesize (i) that K will be greater in the canopy than in the intercanopy; (ii) that at the unit level, K will be similar for the two canopy hydrologic functional units, but in the intercanopy, it will be higher for the herbaceous hydrologic functional units than for the bare ones; (iii) that at the intercanopy locus level, K will be greatest for the grass, followed by the biological soil crust, and then by the bare soil.

MATERIALS AND METHODS

Mesita del Buey is a 5-ha area located on the Pajarito Plateau within the Los Alamos National Laboratory. It is situated on a mesa top (slope gradient $<5\%$) from which runoff drains into an adjacent canyon system. These canyons carry water eastward from the Jemez Mountains toward the Rio Grande (Reneau, 2000). The defining feature of the Pajarito Plateau is its thick deposits of volcanic ash, commonly referred to as the Bandelier Tuff, which were laid down by eruptions from the adjacent Jemez Mountains beginning some 1.2 million years ago (Izett and Obradovich, 1994).

The semiarid, temperate mountain climate has been described by Bowen (1990, 1996). The long-term average annual precipitation at Mesita del Buey is around 400 mm yr^{-1} (varying with elevation from about 330 to 500 mm yr^{-1}) and displays a strong maximum in the months of July and August. About 40% of total precipitation occurs during July, August, and September, a period often referred to in the region as the summer monsoon. Rainfall during the monsoon period is typically spatially variable and can be locally intense.

A detailed description of the Mesita del Buey soils has been provided by Davenport et al. (1996). Soils at the site are predominantly sandy loam or loam in texture and have developed in Bandelier-Tuff-derived alluvium and residuum. The subgroups Typic Haplustalfs and Lithic Ustochrepts make up about 90% of the soils. The major difference between these two subgroups is that in the Haplustalf soils, the B horizon is much better developed.

At the study site (elevation 2140 m), the dominant tree species are Colorado piñon pine and one-seed juniper. Tree density for both species is about 684 trees ha^{-1}, with approximately 55% of the area being covered by trees (Martens et al., 2000). Along a transect within the study site, the average length of canopy patches was 4.5 m and the average length of intercanopy patches was 5.4 m (Breshears et al., 1997a). Piñon trees exceeding 1 m in height range in age from about 50 to 230 yr, with an average of 135 yr (Davenport et al., 1996). About 20% of the intercanopy areas are bare; the rest of the intercanopy is covered by litter, biological soil crust, and herbaceous vegetation. The dominant herbaceous plant is blue grama (*Bouteloua gracilis* [H.B.K.] Lag.).

Using ponded (Prieksat et al., 1992) and tension (Ankeny, 1992) infiltrometers having a 76.2-mm-diam. base, we determined K_s for ponded conditions and $K(h)$ for selected soil water tensions (30, 60, and 150 mm) at 71 locations within the Mesita del Buey study area (a total of 284 measurements). At each location, the measurement was continued until steady state was achieved.

All of the measurements were made within sites selected to correspond to the hydrologic functional units at the unit level: juniper canopy (three trees), piñon canopy (three trees), herbaceous vegetation (three sites of approximately 2–3 m^2), and bare ground (three sites of approximately 2–3 m^2). These sites, twelve in all, were scattered throughout the 5-ha Mesita del Buey study site. Sites were selected on the basis of being representative of a particular unit (juniper canopy, piñon canopy, herbaceous vegetation, or bare ground) in our conceptual model. The canopy sites that we selected for study had trees of medium to large size and thus were in the upper 66% of the tree-size distribution (Martens et al., 1997). Measurements were made at five locations under each tree, nine locations in each vegetated intercanopy area, five locations in two of the bare areas, and six locations in the third bare area. Measurements from two locations (one within the juniper canopy and one within the herbaceous intercanopy) were discarded because of suspected measurement error. Within each of the herbaceous intercanopy sites, samples were further stratified as grass, biological soil crust, and bare spot. Biological soil crust locations were identified on the basis of visual indicators. The number of sites and measurement locations sampled for each hydrologic functional unit are shown in parentheses in Fig. 1.

Measurements were made in accordance with procedures outlined by Ankeny (1992). At each location a sharpened ring (76.2-mm in diameter) was inserted a few millimeters into the soil, and the soil surface within the ring was prepared with the minimum disturbance possible. Under tree canopies, the litter and duff layer was completely removed to expose bare soil. Within intercanopy areas, litter and rock were removed and vegetation was clipped to ground level. Biological soil crusts were not removed. Our measurements, therefore, directly reflect the influence of physical and biological soil crusts at the soil surface, but not of aboveground vegetation. The ponded infiltrometer measurements were made first, to determine K_s, after which a contact sand layer was applied to the ground surface and leveled. Then tension infiltrometer measurements were done, from low to high tension (Mohanty et al., 1994). The relationship developed by Ankeny et al. (1991) was used to calculate the hydraulic conductivities corresponding to the different tensions.

Determining K at different tensions allows one to estimate the relative importance of macropores to the movement of water into and through the soil (Mohanty et al., 1994; Wilson and Luxmoore, 1988). According to capillary theory, infiltration at tensions of 30, 60, and 150 mm will exclude pores with diameters equal to or larger than 1, 0.5, and 0.2 mm, respectively. The difference in infiltration rates at different tensions, therefore, is an indication of the relative magnitude of potential water flow through different pore-size classes. According to the classification by Luxmoore (1981), macropores have diameters >1 mm, and micropores have diameters <0.01 mm. Pores that fall between these two sizes are referred to as mesopores. Although others have defined macropores as those draining at tensions below 150 mm (Ankeny et al., 1990; Mohanty et al., 1994), for our study we have followed the system of Wilson and Luxmoore (1988): we consider the difference in infiltration between ponded conditions and a tension of 30 mm as representing macropore flow, and the difference in infiltration between tensions of 30 and 150 mm as representing mesopore flow.

The data for K_s, K_{30}, K_{60}, and K_{150} were analyzed separately in the following manner. At the patch level, a *t* test, using the site-level means as data points, was performed to test the null hypothesis that the mean of the distribution underlying the canopy measurements is the same as the mean of the distribution underlying the intercanopy measurements. At the unit level, a one-way analysis of variance, again using the site-level means as data points, was used to test the null hypothesis that the means of the distributions underlying the juniper, piñon, herbaceous, and bare units are the same. Comparisons between all the different combinations of means were made using the Tukey-Kramer multiple comparisons method. At the intercanopy locus level, a randomized complete block ANOVA was used to test the null hypothesis that the means of the distributions underlying the grass, biological soil crust, and bare spot measurements within the herbaceous units are the same. Tukey's one degree of freedom for non-additivity test was used to test the null hypothesis that there are no multiplicative interactions between the site factor and the plant type factor. Comparisons between all of the different combinations of means were made using the Tukey-Kramer multiple comparisons method. Significance was determined at $P = 0.05$. To better meet the modeling assumptions, for some combinations of the outcome variable and test, the log transformation was applied to the data before the test was completed.

RESULTS

At the patch level we found that both K_s and $K(h)$ were greater for the canopy patches, but the differences were significant only for $K(h)$ (Tables 1 and 2). Saturated hydraulic conductivity (K_s) median values for locations within the canopy and intercanopy patches were about the same. The upper range in K_s values, however, was considerably higher for the canopy than for the intercanopy (Fig. 2a).

At the unit level, the higher variability of measurements under the juniper canopy locations relative to locations within other units is noteworthy (Fig. 2b). Most of the high values for K_s, in fact, were recorded under juniper canopies. Of the 14 measurement loca-

Table 1. Average site *K* values for hydrologic functional units for various hierarchical levels. The number of sites (*n*) averaged per hydrologic functional unit is indicated in parentheses.

Hydrolic functional unit	K_s	K_{30}	K_{60}	K_{150}
	mm h^{-1}			
		Patch Level		
Canopy ($n = 6$)	150	29	11	6
Intercanopy ($n = 6$)	73	14	4	2
		Unit Level		
Juniper ($n = 3$)	230	38	14	7
Piñon ($n = 3$)	71	20	8	5
Herbaceous Intercanopy ($n = 3$)	93	18	6	3
Bare Ground Intercanopy ($n = 3$)	51	10	2	2
		Intercanopy Locus Level		
Grass ($n = 3$)	93	20	8	4
Biological Soil Crust ($n = 3$)	107	21	6	3
Bare Spot ($n = 3$)	80	14	4	2

Table 2. Results of tests for determining statistical significance of differences in hydraulic conductivity among patch, unit, and intercanopy locus levels.

HFU comparison†	K_s	K_{30}	K_{60}	K_{150}
	Patch Level			
Canopy/Intercanopy	NS‡	*	*	*
	Unit Level			
Juniper/Piñon	NS	NS	NS	NS
Juniper/HI	NS	NS	NS	NS
Juniper/BGI	NS	*	*	*
Piñon/HI	NS	NS	NS	NS
Piñon/BGI	NS	NS	*	*
HI/BGI	NS	NS	NS	NS
	Intercanopy Locus Level			
Grass/BSC	NS	NS	NS	NS
Grass/Bare	NS	NS	NS	NS
BSC/Bare	NS	NS	NS	NS

* Significant at the 0.05 probability level.
† HFU, hydrologic functional unit; HI, herbaceous intercanopy; BGI, bare ground intercanopy; BSC, biological soil crust.
‡ Not significant.

tions within the juniper canopy, there were four very high K_s readings, three of which were taken under the same tree. Differences in average K_s between the juniper trees were striking, with average K_s being 70, 206, and 413 mm h^{-1} for the individual juniper trees. By comparison, average K_s for the piñon trees ranged from 60 to 92 mm h^{-1}. The next highest values to those recorded for juniper canopy were those for the intercanopy herbaceous units. Saturated hydraulic conductivity (K_s) values were consistently low within the intercanopy bare units. These differences may indicate some trends, but variability among measurements was high enough that differences in K_s were not statistically significant. Differences were significant only for selected $K(h)$ comparisons at the unit level—specifically, juniper–bare ground and piñon–bare ground (Table 2).

At the intercanopy locus level, K values were not statistically different (Table 2, Fig. 2c). Slightly higher K_s was measured for the bare spots (i.e., small bare areas within intercanopy herbaceous units) than for the intercanopy bare units (at the next hierarchical level), suggesting a positive influence from greater proximity to vegetation.

The decrease in K with tension is a reflection of the relative importance of macroporosity (Fig. 2 and 3). For example, at 30 mm of tension, average K_s was reduced by about 80% for all hydrologic functional units, irrespective of level (Table 1). In other words, for ponded conditions, macropores account for around 80% of the infiltration that occurs. Average $K(h)$ at the 60- and 150-mm tensions are around 5% of K_s.

DISCUSSION AND CONCLUSIONS

We found that K_s values tended to be higher under the canopies than in the intercanopy areas, but these differences were not statistically significant. This trend was accounted for largely by a few exceedingly high readings from a few locations under juniper canopies. The values obtained from fully half of the locations were quite comparable. The high values under juniper canopies (and one juniper canopy in particular) may

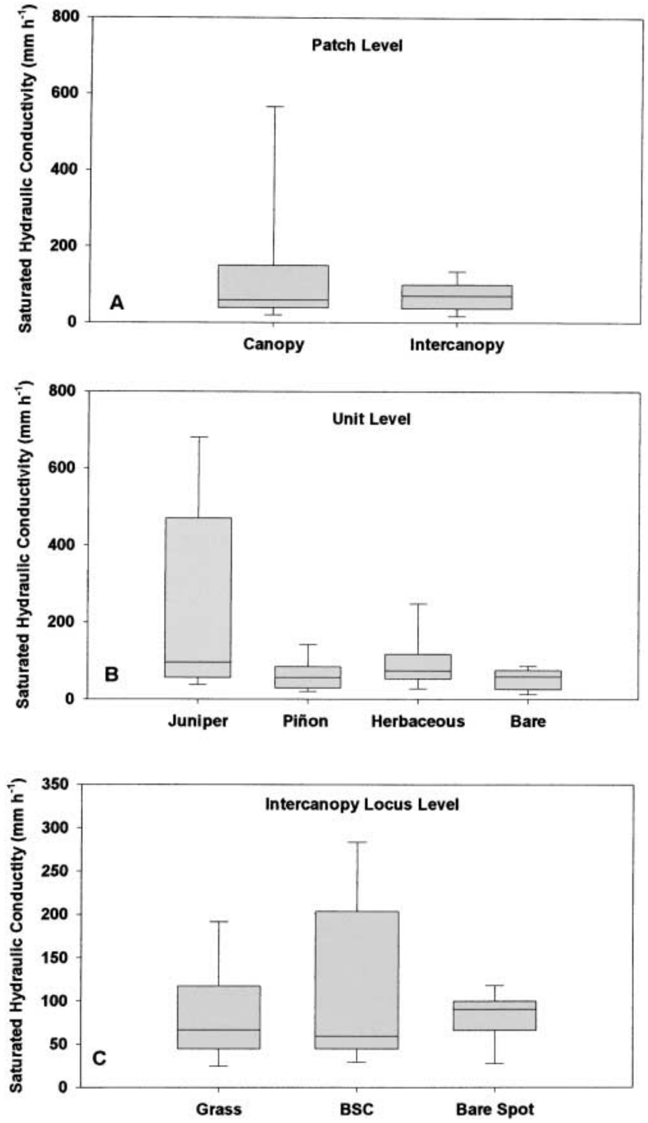

Fig. 2. Box-and-whisker diagrams showing the median, 10th, 25th, 75th, and 90th percentiles for saturated hydraulic conductivity from all measurement locations for hydrologic functional units within the (a) patch level, (b) unit level, and (c) intercanopy locus level.

reflect infiltration via macrochannels (roots close to the surface). Juniper trees are better able to extract shallow soil moisture and probably have a greater number of fine roots close to the surface than do piñon trees (Breshears et al., 1997b), explaining at least in part the higher macropore flow under juniper canopies. The wide variation in K_s among individual juniper trees is interesting and suggests that infiltration characteristics may vary by individual tree; but more measurements would be required to determine this. In any case, the distribution of K_s under juniper canopy is strongly skewed, with K_s being exceedingly high in a comparatively few locations.

Our results, in concert with those of other studies comparing canopy/intercanopy hydrology in piñon-juniper woodlands, would suggest that K_s is not the determining factor for the differences that have been observed in infiltration (Roundy et al., 1978) and in runoff (Reid et al., 1999). Roundy et al. (1978), using small-

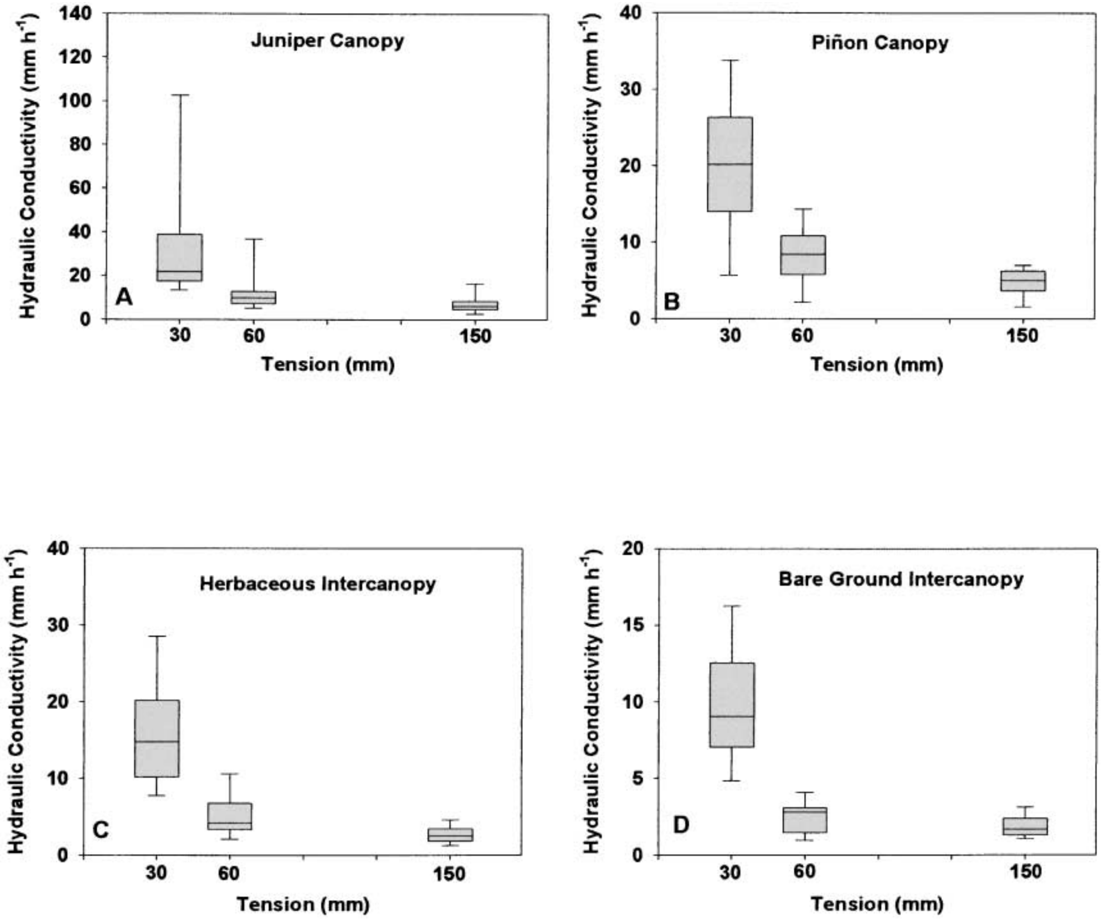

Fig. 3. Box-and-whisker diagrams showing the median, 10th, 25th, 75th, and 90th percentiles for unsaturated hydraulic conductivity from all measurement locations at tensions of 30, 60, and 150 mm for (a) juniper canopy, (b) piñon canopy, (c) herbaceous intercanopy, and (d) bare intercanopy units.

plot rainfall simulation (litter was not removed), found higher infiltration rates under piñon-juniper canopies than in the intercanopy. In contrast, our results did not show consistently higher rates of K_s for the canopy areas. But we measured only the K_s of the soil itself; we did not take into account the effect of litter under the canopy (litter was removed) or of the surface sealing that may be produced by the impact of raindrops. The unsaturated hydraulic conductivity $K(h)$ values, however, were significantly higher for canopy than for intercanopy areas (but relative differences, nevertheless, were small).

Similarly, in earlier work at the Mesita del Buey site we documented much lower rates of runoff from juniper and piñon canopy areas than from intercanopy areas (Reid et al., 1999). We found that runoff from canopy areas was generated only by very intense thunderstorms, and when it was generated, it amounted to only about a third of that from intercanopy areas. Clearly, such a difference cannot be explained by differences in K alone. Other factors must be involved, such as interception of precipitation by the canopy leaves (Young et al., 1984) and retention of moisture by the litter layer beneath.

Much greater relative differences in K between canopy and intercanopy soils, determined using methodologies similar to those of this study, have been observed in other shrublands—largely because the intercanopy soils in those areas have very low infiltrabilities. For example, order-of-magnitude differences in K between canopy and intercanopy soils have been reported for shrublands in Australia (Dunkerley, 2000b; Greene, 1992) and tiger bush in Niger (Bromley et al., 1997).

In the current study we did not find statistically significant differences in K between the intercanopy herbaceous units and the intercanopy bare units, although both the mean and the range of variability were greater for the herbaceous units than for the bare ones. With a greater sampling intensity we might have been able to demonstrate that the differences in K observed here are statistically significant. The results are roughly consistent with the runoff data from earlier work (Reid et al., 1999), which showed runoff from the vegetated units to be about 40% lower than from the bare units. We suspect that the greater surface roughness and increased opportunities for surface storage within the vegetated units contribute as much to lower runoff as do the slightly lower hydraulic conductivities of the soil.

We found little difference in K at the intercanopy locus level, though the biological soil crust showed slightly more variation and higher maximum values than either the grass clumps or the bare spots. At this site, biological soil crust apparently has little effect on soil hydrology, a finding similar to that reported for other sites (Eldridge et al., 1997; Williams et al., 1995). Yair (2001) argues that biological soil crusts affect soil infiltration mainly by reducing the soil-sealing effect of raindrop impact and preventing the development of a physical soil crust, which would reduce the infiltrability of the soil. Because we measured *K* via ponded and tension infiltrometers, our data would not, of course, reflect the effect of surface disturbance caused by raindrop impact.

In combination with the results reported in Reid et al., 1999, those from our current study point to a need for modification of the hydrologic functional unit concept that we have developed for piñon-juniper woodlands (Fig. 1). At the patch and unit levels, real and quantifiable differences in hydrologic characteristics are evident from the differences in *K*, runoff, and erosion between canopy and intercanopy hydrologic functional units. At the patch level, the absorptive capacity of the litter duff under tree canopies contributes to reduced rates of runoff and erosion compared with the intercanopy. At the intercanopy unit level, the higher *K* at discrete locations, greater surface roughness, and greater surface storage potential of the herbaceous units translate to consistently lower runoff and erosion from these areas compared with the bare ones. At the smallest level, the intercanopy locus, hydrologic differences among the hydrologic functional units are so far undetectable. In summary, differences in *K* between the respective hydrologic functional units were not large enough alone to explain the observed differences in runoff related to vegetation patterns (Reid et al., 1999; Wilcox et al., 2003).

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