



Hydrologic effects of dryland shrubs: defining the spatial extent of modified soil water uptake rates at an Australian desert site

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Miniature cylinder infiltrometers were used to quantify the spatial variation of infiltration rates in the soils surrounding some Australian dryland shrubs of the genus *Maireana*. Infiltration rate (f , in mm/h) declined steeply with increasing distance from the stem (d_s in cm), and showed no abrupt change at the position of the overhead canopy margin, whose mean location was 46 cm from the stem. Infiltration rates close to a stem were 3–5 times faster than the mid-interspace value. With data from 14 transects, totalling 76 infiltrometer tests, the radial trend was described by a significant ($p = 0.0001$) power-function model: $f = 98.8 d_s^{-0.527}$. The results indicate gradational change in infiltration rates, and are not consistent with the binary division of shrublands into ‘canopy’ and ‘interspace’ zones. Thus, for shrubs growing sufficiently close together, there may be no interspace soils in the gap between the two canopies. By defining the ‘zone of influence’ of a shrub as that area beneath and adjacent to the canopy and within which the water uptake rate is at least 10% greater than the shrub interspace rate (whose mean was 8.5 mm/h), it is shown that this zone is on average 3.3 times larger than that of the projected canopy area that has traditionally been used as a measure of plant influence. Implications for hydrologic modelling of dry shrublands are noted.

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Introduction

Experimental studies have shown that dryland shrubs are locally associated with soil properties, runoff behaviour and sediment yields that differ from those of nearby soils lacking shrubs (interspaces). Generally, shrub sites show higher infiltration rates, less runoff, and correspondingly less soil loss. For example, using 0.5 m² plots, variously located at shrub or interspace sites in an area of NW Texas, USA, Wood & Blackburn (1981) found that infiltration rates after 30 minutes of rain were highest in shrub canopy sites, which averaged 151 mm/h, 23–60% faster than either shortgrass interspace (60 mm/h) or midgrass interspace (116 mm/h). Wood & Blackburn found soil aggregate stability to be a key term in multivariate regression models of site factors controlling infiltration, and organic matter content was also important.

These results were supported by experimental work on creosotebush performed in New Mexico (Elkins *et al.*, 1986). Using simulated rain at 124 mm/h, this work showed

longer times to ponding for small plots centred on creosotebushes, together with higher infiltration rates and lower yields of eroded sediment. Additionally, nutrients were found to be concentrated near the shrubs, in soils that displayed lower bulk densities as well as more coarse sands and silts than interspaces.

In Idaho, Johnson & Gordon (1988), again using 1 m² plots and simulated rain, found that sagebrush (*Artemisia tridentata*) plots shed less than one-third of the runoff generated on adjacent interspace plots, for initially dry conditions and under identical simulated rain. Shrub plots also released only 12% of the sediment lost from interspace plots. Johnson & Gordon (1988) made the suggestion that the findings of some prior studies (e.g. Blackburn, 1975), in which plots contained mixed shrub and interspace surfaces, are best interpreted not in terms of a direct canopy cover effect. Rather, they suggest that the proportion of soils having shrub or interspace characteristics is what really underlies the data. Factors contributing to the differing soil properties and hydrologic response near shrubs may be grouped into 'direct' effects of the plant, like canopy absorption of raindrop impact energy, and 'indirect' effects, exemplified by the soil changes created by burrowing fauna that prefer the sheltered plant microenvironment. Many, especially the indirect effects, do not undergo abrupt changes at the canopy margins. Rather, they seem likely to decline in intensity with increasing distance from the stem (stem distance) and to exhibit some influence beyond the canopy. However, the extent of this 'zone of influence' of dryland shrubs has not been systematically assessed. This is an important matter to define for the hydrologic and erosional response modelling of shrublands.

The zone of shrub influence extends into the interspaces; a few examples follow. Elkins *et al.* (1986) observed that the roots of *Larrea tridentata* extended into the interspace, as did Gile *et al.* (1998) using excavated specimens of creosotebush and tarbush in New Mexico. In some cases, roots from specimens having canopy diameters in the range 1.2–1.6 m had extended to distances of 4.2–4.5 m from the base of the plant. Therefore, macropores related to root growth and decay must radiate from the stem and into the interspace, but with declining density (see also Kummerow *et al.*, 1977 and Brisson & Reynolds, 1994). In the Australian shrublands, Charley (1971) showed that the influence of saltbush shrubs (*Atriplex vesicaria*), as measured by soil nitrogen abundance, extended across a zone at least three canopy diameters wide. Within this zone, the nitrogen had accumulated from dispersed litterfall. On the basis of these and other data, Charley (1971) argued that the saltbush shrubland he studied in the Broken Hill region should be thought of as being made up of units that consisted of a saltbush shrub and an area of the surrounding surface, with which it interacted.

The only prior study focusing on the decay of these properties with radial distance from a shrub is that of Lyford & Qashu (1969). Lyford & Qashu (1969) used double-ring infiltrometers placed in three positions to assess water uptake rates near creosote bush and paloverde (*Cercidium microphyllum*) at two dryland sites in Arizona. The tests were made close to the stem (designated 'near'), one metre beyond the edge of the canopy ('far'), and half-way from the stem to the far location ('intermediate'). They also reported bulk density and particle-size distribution data. Infiltration rate was found to be highest at 'near' sites, and to decline outward. Infiltration near the stem was 2.6–3 times faster than in the interspace. The 'intermediate' locations, which appear to have been located just within the canopy, displayed rates 1.6–2.4 times faster than interspaces. Bulk density was found to be lower beneath the canopy; more medium sand was also found beneath the creosote bush than in the interspace. The restricted sampling used in this study, and the use of locations fixed not in terms of absolute distance from the stem, but in terms of canopy diameter (which was not reported) make it difficult to resolve the trend of changing properties with distance away from the stem. Nevertheless, in demonstrating that intermediate sites displayed intermediate infiltration rates, Lyford & Qashu (1969) appear to have been the first to demonstrate the existence of gradational change in infiltration rates around dryland shrubs that persisted beyond the canopy and

into the interspace. This finding suggests that the simple model of distinct 'shrub' and 'interspace' hydrologic response, as adopted in the runoff plot studies cited above, may not be in full accord with the field evidence.

Zones of shrub influence extending into interspace soils could partly explain why plant canopy cover has sometimes been found to have low explanatory power in relation to infiltration and sediment production (e.g. Blackburn, 1975). It was the goal of the work reported here to investigate these issues, using a range of soil properties assessed at increasing radial distances from the stems of a series of Australian dryland shrubs. Specifically, the goals were: (1) to discover whether a study shrubland could be partitioned into two distinct subenvironments, interspace and sub-canopy environments, on the basis of distinctly different water uptake rates, or whether there was gradational change between these environments; and (2) to investigate the rate at which any gradational change occurred with distance from the stem of the plant, and use this information to define the spatial dimensions of the shrub zone of influence.

Materials and methods

The study area

Observations were made at the Fowlers Gap Arid Zone Research Station, a pastoral property located in the arid shrublands of western New South Wales, Australia. Fowlers Gap is located 110 km north of the city of Broken Hill, among the low bedrock ridges of the Barrier Ranges. These ranges are composed of sedimentary and meta-sedimentary bedrock of Upper Proterozoic age. The median annual rainfall is 230 mm, falling without a seasonal concentration, both as thunderstorms and as more prolonged rain coming from synoptic-scale depressions moving eastward over the continent. Vegetation is primarily composed of chenopod shrubs, with dominant taxa being the bladder saltbush *Atriplex vesicaria* and various bluebushes (principally *Maireana sedifolia*, the pearl bluebush, and *M. pyramidata*, the black bluebush). On rocky hillsides, there are occasional small mulga trees (*Acacia aneura*), while along major stream channels, all of which are ephemeral, there is often a substantial growth of the river red gum, *Eucalyptus camaldulensis*.

The landscape includes rocky hillslopes flanking the bedrock ridges, which locally rise to 288 m, and gentler footslopes and plains. The rocky hillslopes carry mostly the bladder saltbush, and have blocky surfaces created by the downslope movement of bedrock fragments released from outcrops along the crest line. The footslopes, though often having a veneer of pebbles at the surface, have a much lower stone cover, and more exposed soil material. Often, these gently-sloping landscapes have developed mosaic plant communities, where the shrubs cluster together in patches or contour-parallel bands, with the intervening areas being almost devoid of higher plants (Dunkerley & Brown, 1995). These are runoff-runon landscapes, with a compartmentalized hydrology, where the modified environment among clusters of shrubs is of pivotal importance in encouraging the efficient absorption of runon water from bare areas upslope.

The shrubs

The bluebush shrubs selected for study are the dominant higher plants on the study footslopes. They are woody, perennial plants that grows to about 1 m in height (Cunningham *et al.*, 1981). All of the test specimens were located within a gently-sloping study plot of approximately 30 m × 100 m, and this spatial restriction was designed to limit the greater variability in soils that might be introduced by working over a larger

area. This 0.3 ha plot contained 91 shrubs taller than 60 cm (i.e. approximately one large shrub per 33 m²), and a total of 339 shrubs taller than 10 cm. Locations of all shrubs were mapped using a digital theodolite, and the mean nearest-neighbour distance calculated from a file of shrub coordinates.

Typically, large shrubs sit above a low mound of sandy material that is probably created by the net inward splash of material moved by driving rain (Parsons *et al.*, 1992). There may also be a contribution from dust washed from the leaves following dust storms that are not uncommon in the area, or from dry deposition directly from airborne dust suspension. Using a levelled bar resting on the top of the shrub mound, mound heights were determined as the elevation difference between mound summit and ground elevation at the canopy margin.

Experimental design and methods

The main variable studied here in order to quantify the zone of shrub influence is the water infiltration rate from surface ponding, though other soil properties (bulk density, particle size, and unconfined compressive strength) were also observed. Shrub canopy height and diameter were recorded for each test plant. Detailed observations were made on 14 typical bluebush shrubs selected at locations spread across the 0.3 ha study plot. Around these plants more than 80 infiltration tests were performed. In addition, 63 bulk density and soil water content determinations, made on 500 g samples collected from shallow pits, and 370 observations of compressive strength were performed. Samples for particle size analysis were gently crushed, wet-sieved to separate sands, and analysed for silt and clay content by the pipette method (Gee & Bauder, 1986). Observations of the soil parameters were made on linear transects running 1–3.5 m outward from the shrub stem, with observations made at 20 cm intervals along the transect. Supplementary interspace data were collected from the mid-point of the line joining adjacent pairs of shrubs. In the study area, shrubs are typically 3 m apart, but are not evenly distributed, with gaps of 10 m separating many plants, so that shrub interspace data reported here were in some cases collected at distances of 3 m–4 m from the nearest shrub, in the middle of the interspace.

Measurement of water uptake rate

Owing to the need to make measurements beneath the shrub canopy, a method suitable for use in confined space had to be selected. This also had to be capable of making multiple measurements within 30–50 cm, the typical radius of bluebush canopies. Miniature single-ring disk infiltrometers were therefore used. Because shrub interspace soils often carry a surface crust, and mound soils have fragile sedimentary layering, it was decided that rings would be bonded to the surface to protect fragile or brittle structures, rather than hammered into the soil. Interspace crusts include inorganic (rainbeat) crusts and extensive cyanobacterial crusts, dominated by *Microcoleus vaginatus* (D. Eldridge, NSW Department of Land & Water Resources, pers. comm.), and some lichen crusts. The cyanobacterial crusts in particular have a play character, and break in a brittle way if any attempt is made to dig through them. The infiltrometer rings were therefore made of a very heavy grade of PVC pipe, with inside diameter of 10 cm and a 1 cm wall thickness, cut into cylinders 5 cm tall. The substantial wall thickness provided a broad contact for bonding with the soil surface. The base of the ring was heavily coated with a commercial silastic caulking compound, and gently pressed against the surface until some compound was extruded from beneath the ring. Then an additional bead of silastic was applied around the outside of the ring to ensure that a completely watertight seal was created. This typically gave a 15 mm-wide silastic contact with the soil, which proved to be watertight in all but four instances where small

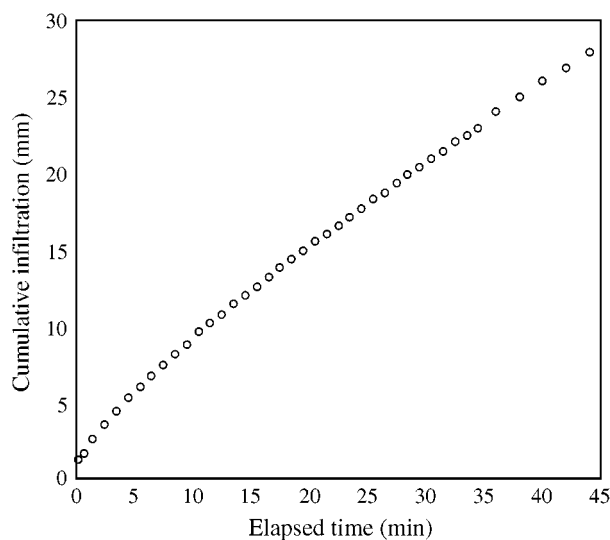


Figure 1. An example of the behaviour of infiltration from one of the miniature cylinder infiltrometers though a 45-minute experiment. Though slightly more rapid at first, the water uptake rate reaches a steady rate after about 20 minutes.

leaks were detected. Data from these tests was discarded. On the flanks of shrub mounds, the infiltrometer rings had to be installed parallel to the slope of the mound. Consequently, the ponds created within the rings were of uneven depth, though the steepest gradient on the flank of a mound was about $7-8^\circ$, so that the effect was not severe. Furthermore, Fox *et al.* (1998) have recently shown that such changes in head have only a minor effect on water infiltration.

Once installed, infiltrometer rings were left for the sealant to cure. Subsequently, an electronic water-level monitor with sharp needle-point probe was set up over the ring, and positioned so that a circuit was opened (sounding a buzzer) when the depth of the initial pond water fell below its starting value of 10 mm. This eliminated bias from the test procedure, and was especially helpful for tests located under dense shrub canopies, when visual monitoring of the water level was not readily possible. Sufficient water to restore the water level and close the electronic circuit was then carefully added from a wash bottle, and the elapsed time noted. The wash bottle was then weighed, and the volume of water determined from the change in bottle weight. Experiments were run in this way for typically 30 minutes, but for up to 1 hour in several cases, until a steady rate of water uptake was reached. The electronic depth probes were quite sensitive, so that pond level was maintained at 10 ± 1 mm, and cumulative infiltration was typically recorded every 60 seconds. After each test, the soil beneath the infiltrometers was excavated, and the depth and pattern of spreading of the wetting front described. A typical set of infiltrometer data (for a test run at 60 cm from the stem of bluebush 3) is presented in Fig. 1, and illustrates a steady rate of water uptake rate beyond about 15 minutes into the trial. Most tests revealed a similar degree of linearity in the water uptake data. The final infiltration rate for statistical analysis was assessed from the slope of the regression line fitted to the cumulative infiltration depths and elapsed time, using only the last 10 minutes of each experiment.

Correction of infiltrometer results for lateral seepage

There is three-dimensional seepage from a single ring infiltrometer, and this is enhanced if the device is attached to the surface, as was done here, rather than embedded (e.g.

Reynolds & Elrick, 1991). Lateral water movement was revealed in the field by a visible wetting front spreading beyond the outer wall of the ring, darkening the soil surface. This is not leakage, but the expected behaviour of water uptake under these conditions (Reynolds, 1993). In order to approximate the saturated infiltration rate K_{sat} correctly, the volume of water uptake into lateral seepage must be allowed for, so yielding an estimate of the vertical water movement into the soil. In one sense, the application of a correction for lateral seepage is not critical in the present work, where the focus is on radial trends in water uptake rates than their absolute values. Nevertheless, given the magnitude of the possible overestimation of K_{sat} that is possible (noted below), it was decided to implement a correction. The use of 'double ring' infiltrometers with a surrounding buffer of water, though often employed in an attempt to minimize this source of error, is known not to provide a correct solution to the lateral seepage problem (Reynolds, 1993). Further, double ring apparatus would have become too large for the radial transects beneath the shrub canopy that had to be made in the present work.

In addition to the issue of lateral seepage, some air entrapment occurs in the soil beneath shallow ponds that are created rapidly. Consequently, ponded measurements determine the hydraulic conductivity at what has been termed '*field saturation*', which is lower than that at complete saturation owing to the obstruction of some pore space by air bubbles. The data will therefore, in principle, indicate a slightly lower value, K_{fstat} , than would laboratory determinations made on undisturbed soil cores, which could be slowly saturated from below. This is accepted here, because the primary goal was to find a parameter which, measured consistently, would reveal variation in the properties of the soils in the radial transects around shrubs. In any case, the presence of buried stones, fragile surface crusts, plant roots, and collapsible faunal burrows all make the collection of 'undisturbed' cores almost impossible in the study soils, so effectively prohibiting laboratory-based analyses. Furthermore, in intense dryland storms, it seems probable that rapid development of surface ponding would ordinarily wet the soil rapidly from above, so effectively restricting hydraulic conductivity to the K_{fstat} value, and in effect mimicking the effects that arise during ponded infiltration tests.

Various workers (e.g. Buttle & House, 1997) have adopted lateral seepage corrections for K_{fstat} that can be applied to data collected using single ring infiltrometers, and based on the method of Reynolds (1993). However, these rely on fitting parameters whose values are unknown in stratified and crusted soils like those of the shrub and interspace soils studied here.

A straightforward geometric approximation for seepage that is based on the form of the wetting front as observed in post-test excavations is therefore employed here in order to avoid the need for the selection of untested parameters. Post-test excavations showed that the wetting front had migrated approximately equal distances laterally away from the inner wall of the infiltrometer as vertically below it. Migration distances were typically 7–10 cm during a 30–45 minute test. The volume of soil thus wetted is composed of the cylinder of soil lying directly beneath the infiltration ring, together with the additional annulus of soil surrounding this that arises from lateral seepage (Fig. 2). The wetting front can then be approximated by a part of the surface of a sphere whose diameter is somewhat larger than the diameter of the wetted zone visible on the soil surface. The wetted volume of soil can be thought of as an inverted cap of this larger sphere.

The diameter of the larger sphere was estimated by plotting on graph paper a scale drawing representing a cross-section of the wetting front (using dimensions recorded in the excavation made at the end of each test), and using standard geometric constructions to find its centre and diameter. The volume of the wetted soil 'cap', V_{cap} , can then be found from the relation:

$$V_{\text{cap}} = \pi h^2 \left(r - \left(\frac{h}{3} \right) \right), \quad (1)$$

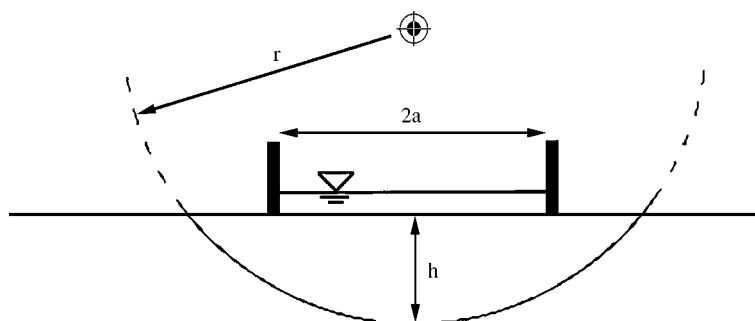


Figure 2. Schematic diagram of the geometric analysis of the area of wetted soil beneath a cylinder infiltrometer at the conclusion of a test. Symbols are explained in the text.

where h is the depth of the wetting front vertically below the infiltrometer, and r is the radius of the larger sphere to which the 'cap' is fitted. The fraction of this cap volume that is represented by the wetted soil lying vertically beneath the infiltrometer, V_{cyl} , can readily be calculated from:

$$V_{cyl} = \pi a^2 h. \quad (2)$$

Analysis of the enclosed volumes V_{cap} and V_{cyl} for the case of a symmetrical wetting front (one that has reached the same distance laterally as vertically into the soil) shows that the total amount of water taken into the wetted soil is approximately 4.4 times that contained in the cylinder vertically beneath the infiltration ring, and which would be recorded had only vertical infiltration taken place from the base of the surface pond. Writing this result in the same form as that derived from the work of Reynolds (1993) yields the relation:

$$K' K_{fstat} / 4.4, \quad (3)$$

or equivalently:

$$K' = 0.23 K_{fstat}. \quad (4)$$

In these equations, K' is the estimate of K_{fstat} that is derived following the correction for lateral seepage. The uncorrected values are about 4.4 times too large.

Data analysis

To develop a model describing the variation of infiltration rates with stem distance, all the raw data were grouped into classes (0–20 cm stem distance, 20–40 cm, etc). The mean infiltration rate for each class was then regressed against the mid-point stem distance of that class. However, variance was not uniform across all classes, greater variability being shown by those nearer the stem. Accordingly, a weighted regression model was developed using the Regress + mathematical modelling routines (McLaughlin, 1998). This scales the residuals from the regression model by dividing by the class standard deviation for that interval, and so in essence attaches less importance to data points whose position is less certain because of high standard deviation in the data, and more strongly fits the regression line to the points whose associated standard deviation is smaller.

In all of the results that follow, the infiltration rate, expressed in units of mm/h, is the given the symbol f , and the stem distance, expressed in cm, is given the symbol d_s .

Results

Results for shrub and soil properties are presented first, followed by those for infiltration behaviour in the shrub and interspace environments.

The shrubs

For the 91 large shrubs, the mean nearest-neighbour distance was 3.0 m. Mean shrub height was 65.5 cm (S.D. 18.4 cm) while the mean canopy diameter was 92.2 cm (S.D. 33.9 cm). The shrubs exhibited constant growth proportions, the correlation coefficient of height and diameter being 0.86. The mean height of the shrub mounds from a sample of 20 specimens was 4.1 cm, and the maximum was 6.0 cm

Soil properties

Gravimetric water content

At the time of testing, the soils were very dry, having gravimetric moisture contents of < 5%. Soil water content was not related to stem distance.

Particle size characteristics

The shrub mounds are composed of distinctively coarse materials. The dominant component was sand (72.8%), with smaller components of silt (14.3%) and gravel (10.3%), but almost no clay (0.9%). This composition may be compared to the mean of interspace samples, which have less sand, but more silt and clay (means were sand, 56.3%, silt 26.4%, and clay 3.1%).

Water uptake rates

Infiltration rates were most rapid close to shrub stems, and all 14 test shrubs showed values of f that declined with increasing stem distance. There was at the same time substantial variability in rates both beneath the canopy and in interspaces. Rates approached 40 mm/h within 50 cm of a stem and declined to 5–10 mm/h in mid-interspace, several metres from the nearest shrub. The increase in infiltration rate nearer to a stem was rapid, and for locations within about 1–1.5 m of a stem, the trend was found to be best described by a log-log (power function) model (Fig. 3). For Test Shrub 1 (Fig. 3(a)), the fitted relation was $f = 1326.1 d_s^{-1.26}$, while for Test Shrub 6 (Fig. 3(b)), it was $f = 122.7 d_s^{-0.49}$. Both equations are significant at $p = 0.05$ level.

When the entire data set of 76 test results was examined, including the mid-interspace sites at stem distances of up to 3.5 m, it was found that again the best fit was a power function model, the equation for which is:

$$f = 98.8 d_s^{-0.527}. \quad (5)$$

This relationship has $r^2 = 0.28$ and is statistically significant ($p = 0.0001$).

Using the weighted regression procedure on grouped data, a relationship similar to that found from the ungrouped data was developed, but in this case with considerably improved fit (Fig. 4).

The results suggest that the poorly-conditioned regression of the 76 ungrouped infiltration and stem distance pairs, where variance is not constant with stem distance,

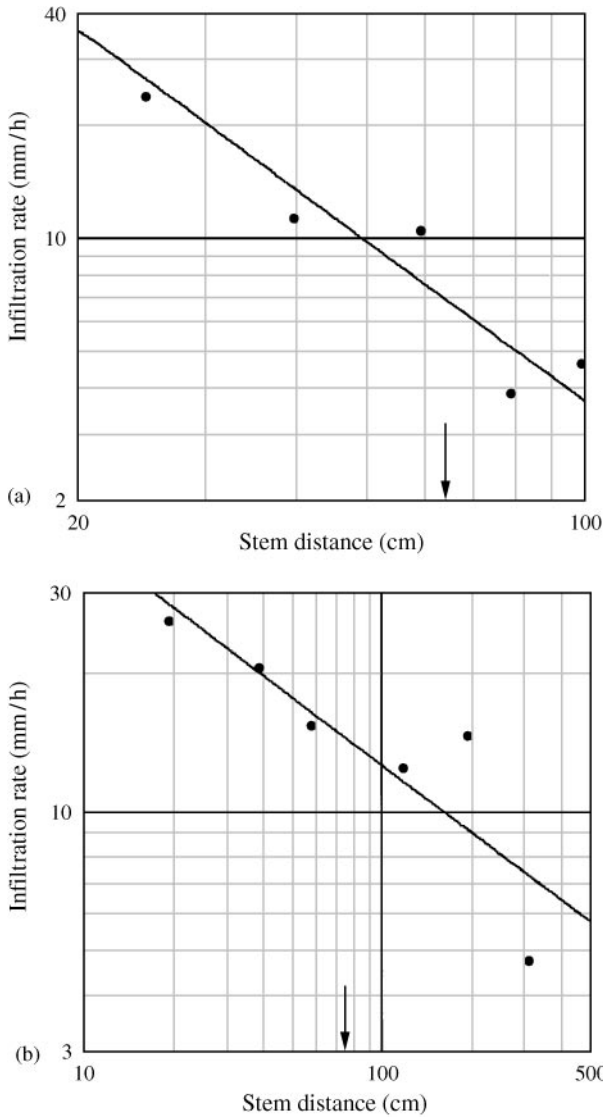


Figure 3. Plot of the regression relationship between natural logarithm of infiltration rate (mm/h) and natural logarithm of stem distance (cm) for two typical test specimens of bluebush. Regression equations are provided in the text. Arrows on the diagrams show the position of the shrub canopy. (a) Test shrub 1; (b) Test shrub 6.

overestimates infiltration rates close to the stem by about 10 mm/h, the error declining to about 1 mm/h at a stem distance of 100 cm. The relevant adjusted regression models is:

Weighted least-squares based on grouped data transformed by taking natural logarithms:

$$f = 139.4 d_s^{-0.61} \quad (r^2 = 0.94, p = 0.0001). \tag{6}$$

It is now possible to make a first estimate of the zone of influence of the shrubs. The mean canopy radius of 46.1 cm means that a typical shrub canopy covers 0.67 m² of the soil surface. Thus, the canopies of the 91 large shrubs in the study plot cover in total only

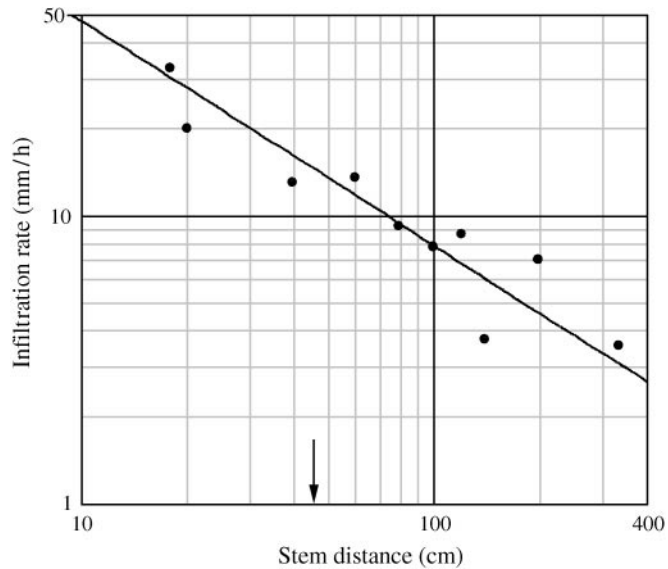


Figure 4. Plot of the regression relationship between natural logarithm of infiltration rate (mm/h) against natural logarithm of stem distance (cm), for the whole data set of 76 results grouped into 10 stem distance classes. The arrow marks the mean stem distance of the edge of the shrub canopy. The relevant equation and other details are provided in the text.

about 2.0% of the area. Zones of the soil surface where infiltration is significantly enhanced owing to the proximity of a shrub are here defined as those where the infiltration rate is at least 110% of the mean value for mid-interspace sites. Using the 14 tests carried out at distances of 1.2–5.0 m from a shrub, the mean infiltration rate is 8.4 mm/h. If sites 1 m or more distant from a stem are included, the mean of the 24 tests is 8.5 mm/h. Therefore, a value of 8.5 mm/h is adopted as a suitable measure of the interspace rate. (For comparison, the mean rate for the 10 sites within 20 cm of a stem is 22.2 mm/h.) Linear regression with infiltration rate as the independent variable and stem distance as the dependent yields the model:

$$d_s = 3261.7f^{1.637} \quad (r^2 = 0.92, p = 0.0001). \quad (7)$$

Using this, the stem distance at which the infiltration rate falls to 9.35 mm/h (i.e. 1.1×8.5 mm/h) is 84 cm. This then is adopted as the radius of the zone of influence of a typical shrub, which consequently covers an area of 2.22 m², or 3.3 times the area directly covered by the canopy itself.

The 91 large shrubs then exert a significant influence on infiltration over an aggregate area of 202 m², or 6.7% of the 0.3 ha study plot. Whilst a few shrubs are located so closely together that their zones of influence overlap, making the above estimate of their total area an overestimate, the mean nearest-neighbour distance of 3 m exceeds the inferred radius of the zone of influence (0.84 m), so that as a first approximation, the figure of 202 m² can be accepted.

Discussion and conclusions

The results have shown that the test shrubs typically sit above mounds of relatively coarse sediment. The mean mound height (6 cm) is very similar to the 4 cm reported for *Larrea tridentata* (creosotebush) and for *Fluorensia cernua* (tarbush) at the Jornada

Range in New Mexico (Gile *et al.*, 1998). In contrast, Parsons *et al.* (1992) measured mounds up to 20 cm for *Larrea tridentata* at Walnut Gulch in Arizona. These higher pedestals owe their greater size in part to the scouring and lowering of interspaces by surface runoff. Texture of the mound materials in the present study (largely sand, with accompanying silt and minor gravel) also resembled that reported by Parsons *et al.* (1992) for surface materials on the mounds associated with the shrub *Nolina microcarpa*, which were also dominantly composed of sand (81–87%), with 8–12% silt and 5–7% clay. Gravel, if present, appears to have been excluded from these figures. In the present work, trends of progressive compositional change from shrub mound to interspace were noted. Sand content declines with increasing radial distance, while silt content increases. This may be inferred to arise from progressive insplash of sand materials that lodge in the shelter of the canopy, and possibly washout of fines into the surrounding interspaces in occasional runoff from the shrub mounds. Gravel content is uniform across these environments, and this suggests that it is immobile in splash or wash on the low gradients of the study site (approximately 1.5°).

Infiltration rates were found to decline away from the shrub stem, exhibiting a gradational change with no break at the position of the plant canopy margin. The sandier texture of materials surrounding the shrub provides one reason for the enhanced infiltration rates measured there. The lower interspace rates are in accord with the observation of runoff from these surfaces at the study site during storms of low intensity. Furthermore, rainfall simulation tests on 1 m^2 plots on interspaces close to those tested here have generated very similar rates. Five interspace plots exposed to rain at 30 mm/h for 45 minutes, for example, showed final infiltration rates of 8.2, 8.3, 9.8, 10.0, and 14.7 mm/h, yielding a mean value of 10.2 mm/h (standard deviation 2.6 mm/h). As is noted earlier, the mean interspace rate derived from the geometrically-corrected infiltrometers was 8.5 mm/h. Though no rainfall intensity data are available for the study area, thunderstorm rain intensities seem likely to exceed the infiltration rates that are displayed in the interspaces, and less frequently those of the shrub mounds. Further, though some of the infiltrometer tests were run for 1 hour, only rare storms would be able to satisfy the canopy interception of these shrubs, and then continue to deliver water to the surface by drip for a continuous period of this length. In other words, the rates measured can be sustained for periods at least as long as the likely duration of throughfall under shrub canopies, and can therefore be taken as representing the storm-period behaviour of these soils.

These water uptake rates are indicative of a gradational change in hydrologic response from sub-canopy to open interspace. Some of the factors likely to be responsible (such as radially diminishing density of root occupation of the soils) were considered earlier, and other can be envisaged, but many require explanatory work so that their role can be confirmed and their contribution to the measured zone of influence quantified. These include chemical and textural differences between shrub and interspace soils (Charley & West, 1975; Virginia & Jarrel, 1983); more abundant faunal macropores in the vicinity of a shrub and its root system (Elkins *et al.*, 1986; Eldridge & Robson, 1997); the altered local microclimate (Blackburn *et al.*, 1992); altered soil structure near shrubs related to elevated levels of organic matter (Wood & Blackburn, 1981; Bedunah & Sosebee, 1986); to chemically-enriched stemflow (Whitford *et al.*, 1997), and to more abundant litter near shrubs that may absorb water or slow runoff (Elkins *et al.*, 1986). Different soil water levels near shrubs, arising from concentrated stemflow delivery, shaded microclimate, canopy interception, and plant water use, may also directly affect the values of soil hydraulic properties through the linking of water content, soil suction, and hydraulic conductivity (Elkins *et al.*, 1986).

Radiating roots would result in a declining abundance of root spaces within the regolith, and litter would be dispersed outward in declining amounts. The fate of wind-blown dusts, probably transported in significant quantities in the study area, is unclear. These seem more likely to accumulate in sheltered air in and around shrubs

than in exposed interspaces. Dominantly silt-sized material typically makes up wind-blown dust, but significant quantities of clay-sized particles are also transported (e.g. Nickling, 1983), so that deposition may contribute to the differentiation of the texture of the uppermost regolith.

Another contributor to altered soil properties in the zone of influence is organic matter. Scattered shrubs provide virtual point-sources of organic litter, composed of leaves, flower parts, and small broken pieces of stem. Laboratory tests (Geddes & Dunkerley, 1999) have shown that when dry, this material can be transported by splash caused by gravity drops falling from heights typical of shrub canopies (and striking the ground at less than their terminal velocity). Thus, while runoff beneath shrubs seems likely on occasions, and could wash out litter particles, dispersal of litter initially by splash, and then with wider dispersion by wash, is probably also involved. Again it seems reasonable to infer a declining arrival rate of transported organic detritus with increasing radial distance from the point source (the shrub) as splash and wash trajectories disperse the material. Sites in mid-interspace, therefore, probably receive very low amounts of organic material that could be incorporated into the regolith, and perhaps lose in surface runoff a larger proportion of the organic matter that does arrive, but nearer to a shrub there would be a greater litter fall and less would be lost. Charley & West (1975) emphasized that reported concentrations of salts and nutrients beneath shrub canopies in Utah must reflect a depletion in the levels of these materials in the surrounding soils, and thus emphasized an inward flow of plant nutrients and other materials, which they termed a 'redistribution of capital'. Both the outward spreading and inward concentration scenarios are consistent with a gradational change in regolith properties with stem distance, and not with a binary division of the landscape into 'shrub' and 'interspace' zones.

This indeed is the primary conclusion of the work reported here. The zonation of the surfaces studied is not sharp, but gradational. Where neighbouring shrubs are close together, the zones of influence of adjacent shrubs can in principle overlap, though when shrubs compete for the same volume of soil, much depends on the mechanisms of root interaction (e.g. Schenk *et al.*, 1999). Overlapping 'zones of influence' would result in reduced gradients away from the stem of each shrub along the line joining their centres, and for some distance surrounding this.

The implications of the findings presented here for hydrologic field experiments and for hydrologic modelling based upon shrub and interspace runoff plots seem potentially important. Small plots surrounding individual shrubs (of the kind reviewed earlier) may effectively capture the hydrologic response of only the central part of the shrub zone of influence. Many workers have used plots of 1 m² or smaller, and as noted here, the zone of influence of an average bluebush shrub appears to cover 2.2 m². Likewise, to be regarded as indicative of interspace conditions, small plots need to be located at least 84 cm from the nearest shrub stem, and not merely away from the shrub canopy itself, which may be considerably smaller in diameter. Overall, these considerations suggest that care is needed in the siting of field plots and in the interpretation of hydrologic data derived from them. Similarly, in the hydrologic modelling of arid shrublands, it appears that landscapes need to be partitioned with gradationally changing soil properties in mind.

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