Journal of Arid Environments (2002) **51**: 199–219
doi:10.1006/jare.2001.0941, available online at http://www.idealibrary.com on IDEAL®

Infiltration rates and soil moisture in a groved mulga community near Alice Springs, arid central Australia: evidence for complex internal rainwater redistribution in a runoff–runon landscape

D.L. Dunkerley

School of Geography and Environmental Science, Monash University, P.O. Box 11A, Victoria 3800, Australia

(Received 18 May 2001, accepted 10 October 2001)

Spatial patterns of soil moisture and infiltration rate in a groved mulga woodland in arid central Australia are described. Infiltration rates within groves were measured with miniature cylinder infiltrometers set out in transects radiating from mulga stems, and extending into open sites beyond the plant canopy. Infiltration rates are highest close to stems, and decline rapidly with increasing distance, following a power-function relationship. This pattern of radially declining infiltration means that the soil surface within groves exhibits widely varying infiltration rates that are in some locations indistinguishable from those of intergrove soils.

Contour-normal transects of surface soil moisture content and unconfined compressive strength were run across multiple wavelengths of the repeating mulga grove pattern. Soils within the lower intergroves were indistinguishable from those in the upper parts of groves in terms of these properties. Consequently, the position of the intergrove—grove boundary between these two locations could not readily be accounted for by the observed soil properties. Other factors (such as nutrient availability) may be involved in fixing the position of intergrove–grove boundaries, and this suggests the need for additional investigation of the mechanisms controlling the form of these patterned woodlands.

Keywords: mulga woodland; grove; intergrove; stemflow; infiltration; soil moisture; Alice Springs Australia

Introduction

Groved and banded vegetation communities are abundant in low-gradient arid and semi-arid landscapes globally (Tongway & Ludwig, 1990; Dunkerley & Brown, 1995; Valentin *et al.*, 1999), and this landscape structure makes more water available to the

Corresponding author: Fax: 61-3-9905-2948. E-mail: david.dunkerley@arts.monash.edu.au

0140-1963/02/020199 + 21 $35.00/0

plants growing in relatively dense thickets or *groves* than direct rainfall could supply. Water is shed from the less permeable and less heavily vegetated (or unvegetated) intergroves as surface runoff, and flows downslope to be strongly absorbed in the grove soils. Various water balance studies have suggested that in this way, the groves garner water amounting to perhaps 200% of the open-field rainfall (Cornet *et al.*, 1988). Furthermore, it has been suggested that the better water availability at the upslope side of groves, and the smaller amounts passing through to the downslope edges, leads to the colonization of the lowermost intergrove by pioneer species, and to the gradual death of individuals at the bottom edge. The outcome is thought to be the slow, systematic upslope progression of the whole grove pattern (e.g. Thiéry *et al.*, 1995; Klausmeier, 1999). These mechanisms are here referred to as the 'runoff–runon' view of the hydrology of groved landscapes.

However, in detail the hydrologic operation of these runoff–runon landscapes is more complex than this simple picture would suggest. Intergroves, for example, are composed of a finer-scale patchwork of soils exhibiting differing infiltration properties because of the varying permeability of surface crusts (Bromley *et al.*, 1997).

The soils within groves may also show spatially heterogeneous hydraulic properties. For example, in pioneering work in the central Australian groved mulga (*Acacia aneura*) landscapes, Slatyer (1961, 1965) showed that grove soils had markedly variable infiltration rates, which were high close to the mulga stems but lower in the open. Furthermore, Slatyer (1961, 1965) drew attention to the importance of the upright leaf posture and inward-sloping stem architecture of mulga trees that delivers large volumes of stemflow to the highly absorbing soils close to the stem. These findings established that rather than the survival of groves being consequent upon the additional water supplied from the intergrove upslope, there was considerable dependence on the internal processes of canopy interception and stemflow, together with marked spatial variability of grove soil properties. Unfortunately, few results from the work done by Slatyer in central Australia have been published; the few actual test results known are cited later. One of the goals of the present research was to extend the pioneering work of Slatyer, and to make the results available to the research community.

Studies in other patterned plant communities have shown variability within groves similar to that suggested by Slatyer (1961, 1965). For example, Dunkerley (2000) studied the variation of infiltration rates around chenopod shrubs in the groves of patterned vegetation north of Broken Hill in arid western New South Wales, Australia. The test plants were individuals of the bluebush *Maireana pyramidata*, a perennial shrub that grows to a height of 1·5 m. Dunkerley (2000) showed that each shrub was surrounded by soils that had high infiltration rates close to the stem, but which became less permeable radially outward. The decline in infiltration rate continued smoothly through the position of the edge of the overhead plant canopy, and into open interspace soils. Thus, the notionally strongly absorbing soils of these groves (as envisaged in the conventional 'runoff–runon' mechanism) in fact only exhibit this property relatively close to shrub stems. In the open spaces between the shrubs, the soil infiltration rates are little different from those of the bare intergroves.

The foregoing brief review suggests that both grove and intergrove soils can exhibit spatially variable hydraulic properties. Furthermore, the variability may contain systematic components. In intergroves, this may arise from slope-related changes in crust type and crust thickness across the intergrove, from a largely erosional regime in the uppermost intergrove (leaving erosional and gravel crusts) to a depositional one associated with sedimentation crusts, in the lower intergrove where a flatter gradient may trigger ephemeral ponding (e.g. Casenave & Valentin, 1992; Bromley *et al.*, 1997). At present, no data appear to be available that could indicate whether an erosional regime in upper intergroves can persist, or whether it is eventually replaced by a stable surface condition.

The objective of the work reported here was to examine further the patterns of soil wetness and infiltration capacity in a mosaic landscape. The community studied is a groved mulga landscape of central Australia similar to that investigated by Slatyer (1961, 1965).

Specific goals were to develop a fuller understanding of the spatial variability of infiltration rates in grove soils related to stem distance; to compare measured rates with those of some nearby intergrove soils; and to establish whether the distribution of soil moisture mapped *in situ* was consistent with the mapped pattern of infiltration rates (here determined as the final or equilibrium rate as determined from tests of 20–30 min duration). A secondary objective was to investigate the extent to which soil hydraulic and physical properties, perhaps varying in a complex spatial mosaic in both intergroves and groves, can account for the locations of the clearly defined intergrove–grove boundaries. The underlying purpose of this work was to resolve more clearly the extent to which the study landscape could validly be regarded as a 'runoff–runon' system characterized by two major hydrologic zones whose properties were distinct. The final goal was to employ sequential aerial photographs to resolve whether progressive upslope migration of the grove pattern, as predicted by models of the kind noted earlier, can in fact be demonstrated for these landscapes.

Hydrology in mosaic landscapes and the role of mulga

Mulga (*Acacia aneura*) is a small tree growing to about 5 m in height and found across extensive areas of the Australian drylands. Landscapes containing the grove pattern have been reported from Queensland (Boyland, 1973; Dawson & Ahern, 1973), Western Australia (Mabbutt & Fanning, 1987), New South Wales (Tongway & Ludwig, 1990) and the Northern Territory (Slatyer, 1961), and all cases occur on gently sloping alluvial–colluvial plains. Despite this widespread occurrence, there are only scant data on the distribution of soil water and soil infiltration properties in mulga intergroves and groves, and fewer analyses of how these landscapes evolve and are sustained. Furthermore, there are no analyses known to the writer that offer explanations of the development of non-groved mulga woodlands in some areas, and strongly groved ones elsewhere.

Field observations have demonstrated that intergroves in central Australian mulga country exhibit low infiltration capacities. For example, Goodspeed & Winkworth (1978) reported that an intergrove near Alice Springs shed runoff in all storms delivering >10 mm of rain. Furthermore, 80% of 210 mm of rain received in 6 days ran off. An additional single measurement of an intergrove infiltration rate, $\sim 10\,\mathrm{mm\,h^{-1}}$, has been reported from groved mulga country in central Australia (extracted from Fig. 5 in Slatyer, 1961). From simulated rain in a groved mulga site in north-western NSW, intergrove infiltration rates of only 10–$15\,\mathrm{mm\,h^{-1}}$ were reported (estimated from Fig. 5 in Tongway & Ludwig, 1990). Thus, there is little doubt that considerable volumes of surface runoff are released from intergroves in mulga woodlands, to pass downslope toward the next grove.

The concentrated delivery of stemflow, and its absorption within more permeable soils located around plant stems, has been identified as a second important source of water for Australian mulga groves. Slatyer (1961, 1965) measured stemflow with tree collars, and throughfall with rain gauges. Stemflow was detected from rains of as little as 2·5 mm, and in falls of 12·5 mm, delivered to the tree base a volume of water equivalent to 40% of the rain falling over the projected crown area (Slatyer, 1965). Thus, the canopy of the mulga can transfer water from rain to the soil surface within the grove in smaller rain events than can the intergroves. That is, a larger threshold rain event size is required before runon water is transferred to groves from the neighbouring groves upslope.

Permeable soils near the mulga stems retain the stemflow. Using 300 mm diameter cylinder infiltrometers, Slatyer (1961, 1965) made some determinations of soil infiltration rates, and stated (though without presenting the actual experimental data) that the rates in groves were always $> 18\,\mathrm{mm\,h^{-1}}$ but reached $150\,\mathrm{mm\,h^{-1}}$ close to tree stems. Among the few actual data from this work that have been published are two test results collected near a mulga tree: about $15\,\mathrm{mm\,h^{-1}}$ at a stem distance of 2 m, and $23\,\mathrm{mm\,h^{-1}}$ at a stem distance of 0·5 m (extracted from Fig. 5 in Slatyer, 1961). In an environment where soil properties exhibit this kind of variability, a sample size larger than two measurements is clearly required. This is particularly so in the present work, where, as noted earlier, one objective was to assess the internal uniformity (or lack of it) within the mulga groves.

Additional observations of mulga hydrology have been reported from non-groved woodlands in Queensland, Australia. One study noted that all of the considerable volume of stemflow was absorbed into the soil within 15–45 cm of the tree base, depending on tree size, and that the volume of water funnelled into this small area from the canopy above could amount to 140 mm depth from a 25 mm rainfall (Pressland, 1973). Subsequently, Pressland (1976) used 15 cm double-ring infiltrometers to measure soil infiltration rates at 0·25, 0·5, 1·0, and 2·0 m from mulga stems. Infiltration rates after 5 min of ponding at 0·25, 0·5, and 1 m stem distance were 57, 46 and $34\,\mathrm{mm\,h^{-1}}$ respectively. After 60 min, the rates had declined to 20, 17 and $8\,\mathrm{mm\,h^{-1}}$. No difference was reported between the rates measured at 1 and 2 m stem distances. The rates reported close to the stem are notably lower than $150\,\mathrm{mm\,h^{-1}}$ claimed for central Australian mulga noted earlier. Nonetheless, the work of Slatyer (1961, 1965) and Pressland (1973, 1976) confirm that mulga trees are associated with elevated infiltration rates at locations close to the stem. In the present study, additional data on both intergrove and grove infiltration rates are combined with observations of several soil properties including *in situ* determinations of soil moisture. The resulting data were sought to facilitate an analysis of the nature of water redistribution from intergrove to grove, and in particular to seek aspects of the runoff–runon system that might account for the location of the intergrove–grove boundaries, which are a striking feature of the central Australian landscape (Fig. 1).

Field area and research methods

Environment of the study area

Field observations were made on the southern margin of a gently sloping alluvial plain, the Burt Plain, that flanks the northern side of the Macdonnell Ranges, north of Alice Springs in central Australia (Fig. 2). The study site lies at an elevation of about 700 m. Woodland of mulga is widespread and often takes the form of a mosaic in which the trees occur in dense contour-aligned groves surrounded by intergroves of native and some introduced grasses (Fig. 3). Away from the widely separated ephemeral stream channels that arise in the rocky hill country to the south, no rills or other channels exist, and laterally extensive litter dams within the groves indicate that surface runoff traverses the landscape as shallow unchannelized flow. Large termite

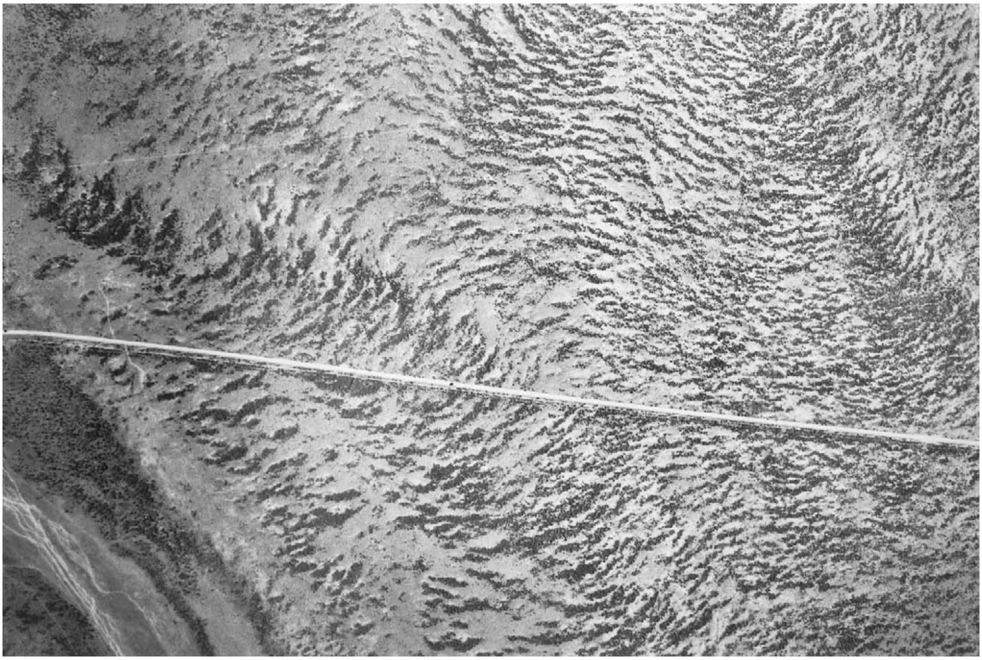

Figure 1. Aerial photograph of mulga groves in the study area. General terrain slope is toward the north (top of the photo). Width of the image is about 5 km. The road visible in the photo is the Tanami Desert road, and Kunoth Bore is located just off the left-hand edge of the image. Photograph copyright Commonwealth of Australia.

colonies occur within the grassy intergroves, and litter is not abundant there. Indeed, in places the intergrove surface carries a veneer of coarse sand and fine granules which appear to be lag deposits left by the downslope removal of finer matrix grains. Within the groves, fallen mulga leaves and dead branches locally supply abundant litter and obstruct flow pathways. Both groves and intergroves carry numerous nests of various species of ants; these probably do not funnel runoff into the soil, however, as the nests are ringed by quite high mounds of excavated soil. However, the underground chambers might be involved in carrying water through the soil under conditions of local saturation. The study area, lying within the Hamilton Downs pastoral property, is presently grazed by beef cattle, a landuse that began in the late 19th century (Low, 1978). The climate is arid, the median annual rainfall at nearby Alice Springs (unfortunately, the nearest meteorological station) being 257 mm (Low, 1978), with a summer maximum. Summers are hot, while winters are cold and dry. Surface water is absent except briefly following rain. The environment has been more fully described by Slatyer (1961, 1965) and by Low (1978).

In the months prior to the fieldwork reported here, unusually high rainfalls had been received. There are no rain gauge stations located near the relatively remote study site, but 100 km away at Alice Springs, record rainfalls were recorded for February 2000 (250 mm compared to median of 17 mm) and again in April 2000 (271·6 mm compared to a median of 3·8 mm). Both the plant foliar cover and soil moisture levels reported later are, therefore, probably well above those ordinarily to be expected at the study site (Fig. 3).

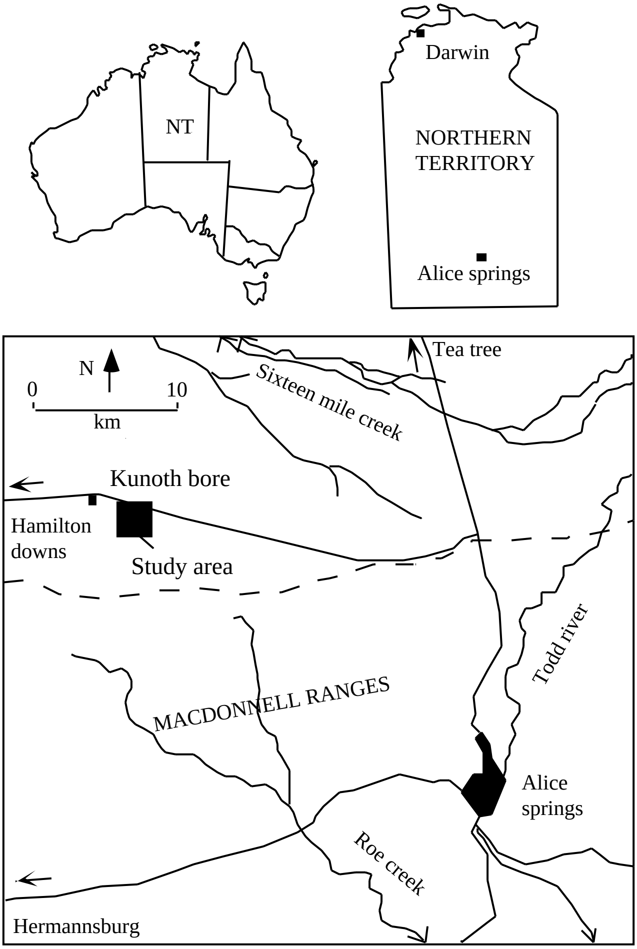

Figure 2. Location of the study area north-west of Alice Springs. The northern limit of the east-west-trending Macdonnell Ranges, marking the abrupt change to low-gradient plains on which the study site is located, is marked by the broken line.

Field data collection and data reduction

Infiltration rates

Infiltration rates were measured using miniature (100 mm diameter) single-ring infiltrometers embedded about 20 mm into the soil. Relatively shallow embedment was adopted in a deliberate attempt to minimize soil compaction or disturbance during cylinder installation. At all test sites, the soil was sufficiently soft that the sharp-edged steel infiltrometer ring could be embedded in the soil using only hand pressure, and therefore little serious fracturing of the soil was likely. An electronic point gauge and piezoelectric buzzer alarm as used by Dunkerley (2000) were installed as an aid to the maintenance of constant water level in the infiltrometer pond, which was topped-up at 30 s intervals from a wash bottle that was weighed on a digital balance to record the volume added. Infiltration tests were generally run for 15 min, but up to 30 min in some cases, and infiltration rates were generally constant for most of this time. Rates were assessed from the last 10 min of data only, using

Figure 3. View along a grassy intergrove in the study area. This intergrove is aligned along the contour, downslope being to the right of the photograph. Width of the intergrove is approximately 15 m.

least-squares linear regression of cumulative infiltrated water volume against elapsed time.

The procedure of Dunkerley (2000) was applied to correct for lateral seepage. This is based on a geometrical approximation of the volume of water that seeps laterally beyond the infiltrometer. The volume of water lost into this annular zone is subtracted from the total infiltrated depth, and this reduces uncorrected infiltration rates by ~75%, yielding very similar results to the somewhat different seepage-correction procedure of Reynolds (1993). There is some uncertainty attached to the correction of any infiltration data, especially at sites where it is possible that some macropore flow (as well as matrix flow) was involved in conducting the water through the soil. Differing proportions of matrix and macropore flow would alter the correction required for lateral seepage. After each measurement, the test site was excavated and the pattern (depth, lateral spread) of the wetting front were recorded. These suggested that in most cases the correction referred to above was appropriate, since a symmetrical bulb of wetted soil indicated quite uniform water movement through the soil matrix. Nevertheless, a tendency was noted for the dimensions of the wetted bulb to differ between bare sites and those close to mulga stems, with possibly less lateral seepage and more vertically directed flow near the trees. However, since the primary interest of the present study is the variability of infiltration rates, rather than their absolute magnitude (which would in any case change through time with antecedent soil wetness, the seasonal growth of plants and the associated changing activity of soil fauna), the application of a consistent measurement protocol is taken to be a sufficient basis for comparison across the banded vegetation community. In any case, the behaviour of three-dimensional wetting in soils is not yet sufficiently well understood to allow the design of an optimum test procedure having no inherent limitations. Intergrove infiltration tests were made at a range of locations selected at random. Within the groves, radial transects were marked out from the trunk of mulga trees and extending outward into open space between the trees. These transects were oriented so that as far as possible, intervals of at least 5 m on either side of the survey line were free of trees whose influence might have perturbed the analysis of the radial distribution of infiltration around the test tree. In all, four trees were studied in detail, with target locations for tests at stem distances of 15, 50 cm, 1·0, 15, 2·5, 4·0, 6·0 and 8·0 m, though in some cases fallen logs or soil disturbance by stock forced the use of slightly different stem distances for some tests. Only one radial transect of infiltration tests was performed at each plant, to avoid statistical bias.

In addition to tests around grove trees, two isolated mulga trees in separate intergroves were examined in more detail. Around one, four radial soil moisture content transects were run outward from the stem to 6 m. The transects were oriented upslope, downslope, and cross-slope to left and right. At the second isolated intergrove tree, a radial infiltration rate transect, using the miniature cylinder infiltrometers, was run in the same way as for the grove mulga trees, and extending out to a stem distance of 3 m.

Soil moisture and other soil properties

Volumetric soil moisture was assessed *in situ* at 1 m intervals along three transects, each running downslope across an intergrove–grove–intergrove triplet, using a commercial dielectric-constant probe (Theta probe; Delta-T Devices Ltd, 1999) whose electrodes extended to a depth of 6 cm below the soil surface. The relationship between the recorded volumetric data and gravimetric water content was calibrated using 100 cm^3 soil samples from the same location, removed with a steel core cutter and dried at 105°C for 24 h. Using the same steel cutter, bulk density was assessed after oven drying according to the method of Blake & Hartge (1986), and later employed to convert the volumetric water contents to their gravimetric equivalents. In order to supplement the *in situ* electronic measurement, bulk density and gravimetric soil moisture were determined every 5 m along one transect extending for 75 m across a grove and the adjoining intergroves upslope and downslope. Soil pH and electrical conductivity were assessed electrometrically using 1:5 soil:water suspensions following the procedure of Rhoades (1982). Soil particle size distributions were determined by wet sieving to separate the gravel and sand fractions, followed by pipette analysis for the silt and clay fractions according to the methods of Gee & Bauder (1986). The unconfined compressive strength (ucs) of the soils was assessed using a Proctor penetrometer, with observations collected at 1 m intervals along the same grove–intergrove transects for which soil moisture data were collected. Along each transect, the measured soil properties were regressed against distance in order to look for statistically significant rising or falling trends in water content and compressive strength with position within each intergrove or grove. Surface cover of grasses in groves and intergroves was assessed using multiple 50 m line-intercept transects oriented randomly with respect to grove orientation, foliar cover being recorded at 1 m intervals.

Temporal change in the locations of intergrove–grove boundaries

Evidence for any upslope progression of the grove patterning was sought from aerial photographs of the area taken 24 years apart (1974 and 1998). The images were scanned, brought to the same scale, co-registered using roads and other fixed features visible in each set of images, and the locations of groves compared. The adjacent sealed roadway is a clear and linear feature, but including a major bend close to the

Table 1. *Details of the individual intergrove and grove widths on mulga transects 1–3. Each transect spans two intergroves ('downslope' and 'upslope') and the mulga grove between them*

Transect number	Width of individual intergroves and groves (m)		
	Downslope intergrove	Grove	Upslope intergrove
1	12·4	22·1	18·0
2	17·7	27·1	32·0
3	16·0	17·0	44·0

study site. These characteristics made orientation of the images straightforward. Maximum error in the registration procedure is assessed to have been 5–10 m (significantly less than the width of the vegetation groves and intergroves).

Results

Dimensions and foliar cover of intergroves and groves

Along the three transects spanning six intergroves and three groves (Table 1), the mean width of the two zones was little different, though intergroves were widest on average (mean width 23·4 m, and for groves, 21·7 m). The widest intergrove (44 m) was larger than the widest grove (27 m).The mean grass cover from five line-intercept transects across intergroves was 50·0% (range 44–62%), whilst within the groves, the mean was 79% (range 70–82%).

Soil texture and other properties

All grove and intergrove samples analysed for texture were sandy clay loams, with 50–60% sand, and about 20% silt and 20% clay. About 1–2% of fine gravel was present in most samples. Soil pH was acid, with a mean of 5·6, and electrical conductivity was low, with a mean of 19·0 $\mu S\,cm^{-1}$ (Table 2). Bulk density determined at 5 m intervals along the 75 m transect spanning a grove and the flanking intergroves upslope and downslope averaged 1·4 $g\,cm^{-3}$. No significant differences were found between grove and intergrove soils for any of these parameters.

Patterns of unconfined compressive strength along two of the transects showed a reciprocal relationship to soil wetness, while one showed a direct relationship (discussed next). Shear strength lay mostly in the range 200–600 kPa, and averaged 432 kPa, whilst gravimetric water content averaged 12·5%. It is likely that some of the measured variation in soil strength is related to variation in soil moisture levels. The spatial variations in soil strength are nevertheless deemed to provide a guide to the level of resistance offered by these soils to splash detachment and to root penetration.

The distribution of soil moisture on grove–intergrove transects

The three intergrove–grove–intergrove soil moisture transects showed complex patterns in which intergrove soils tended to become wetter downslope, whilst grove soils tended to become drier downslope (Fig. 3). The range of soil moisture contents

Table 2. *Summary of soil chemical and physical properties from the study transects ('ucs' indicates unconfined compressive strength)*

	Transect 1		Transect 2		Transect 3		All samples		
Sample statistic	ucs (kPa)	Gravimetric water content (%)	ucs (kPa)	Gravimetric water content (%)	ucs (kPa)	Gravimetric water content (%)	pH	Electrical conductivity ($\mu S\ cm^{-1}$)	Bulk density ($g\ cm^{-3}$)
Mean	333	13·7	421	13·4	543	12·3	5·65	19·0	1·42
S.D.	96	0·78	103	0·78	114	0·88	0·11	4·4	0·08
Number	54	54	78	78	78	78	8	8	16

involved in these patterns was about 6–7%, though repeated fluctuations in soil moisture of 2% recorded over distances of just a few metres make the trends within a grove or intergrove more difficult to identify (Fig. 4). This localized variation in soil properties reduced the correlation coefficient between distance downslope from an intergrove or grove boundary and each soil property to 0·5–0·7. Nevertheless, regression analysis of the trends in soil moisture and compressive strength with distance from the edge of each intergrove or grove (Table 3) showed statistically significant fits (at $\alpha = 0{\cdot}05$) in almost all cases.

These trends are consistent with those suggested by the 'runoff–runon' model, but show that more water is absorbed into the soils of lower intergroves than in their upper parts. Likewise, the patterns indicate that the upper parts of groves receive more water than their downslope parts.

The 75 m profile along which bulk density and gravimetric water content were observed showed the same pattern. Soil moisture rose upslope through the 17 m wide central grove from 12·4% at its downslope edge to a peak of 16·1% at the upslope edge. From this point the 42 m wide intergrove above dried progressively but irregularly, soil moisture declining to 9·5% at its upslope edge.

The four radial soil moisture transects around an isolated intergrove mulga tree showed that the soil was driest near the stem and became wetter with increasing stem distance. Close to the stem, gravimetric water content was 11·5%, rose to more than 13% at 2 m, finally reaching 13·6% at 5 m.

Infiltration rates

The intergroves exhibited a mean infiltration rate of 15·7 mm h^{-1} (range 7·4–30·5 mm h^{-1}). Similar rates were found in the groves, provided that the test site was located more than about 4 m from the nearest mulga stem. At sites closer to mulga stems than this, infiltration rates increased greatly.

The fastest grove infiltration rate observed was 292 mm h^{-1}, for a test site located 15 cm from a mulga stem. In such locations, there was generally a thick carpet of leaf litter, and this was gently brushed aside to allow the infiltrometer to be embedded. The mineral soil beneath the intact litter was highly porous and friable, and clearly greatly enriched in organic matter.

Following the procedure of Dunkerley (2000), radial trends in infiltration with increasing stem distance were described by power-function regression models. These were found to provide a consistently better fit to the data than alternate models such as exponential or logarithmic regression. Analysis of the radial trends in infiltration rate with stem distance (d_s) showed that for three of the four grove trees studied in detail, a statistically significant power-function model adequately described the relationship (Table 3, Fig. 5). The fourth showed a similar but statistically non-significant trend. The data derived from mulga tree #2 (whose basal stem diameter was 26 cm, and height 4·5 m) typify the form of these relationships:

$$\text{infiltration rate}(\text{mm h}^{-1}) = 618 d_s^{-1{\cdot}037}$$

For this relation, which is significant at $\alpha = 0{\cdot}002$, $r^2 = 0{\cdot}87$ (Table 4).

Whilst infiltration rates decline rapidly with increasing stem distance, not even the test conducted at 6 m from the stem of this tree is as low as the lowest of the intergrove test results. Thus, the elevated infiltration rates extend to well beyond the position of the tree canopy. All of the test trees exhibited this smooth power-function decline in infiltration rates across the position of the canopy edge, and into the interspaces within the grove.

The single intergrove tree studied showed the same trends. The radial infiltration rates transect was again adequately described by the power-function model. The

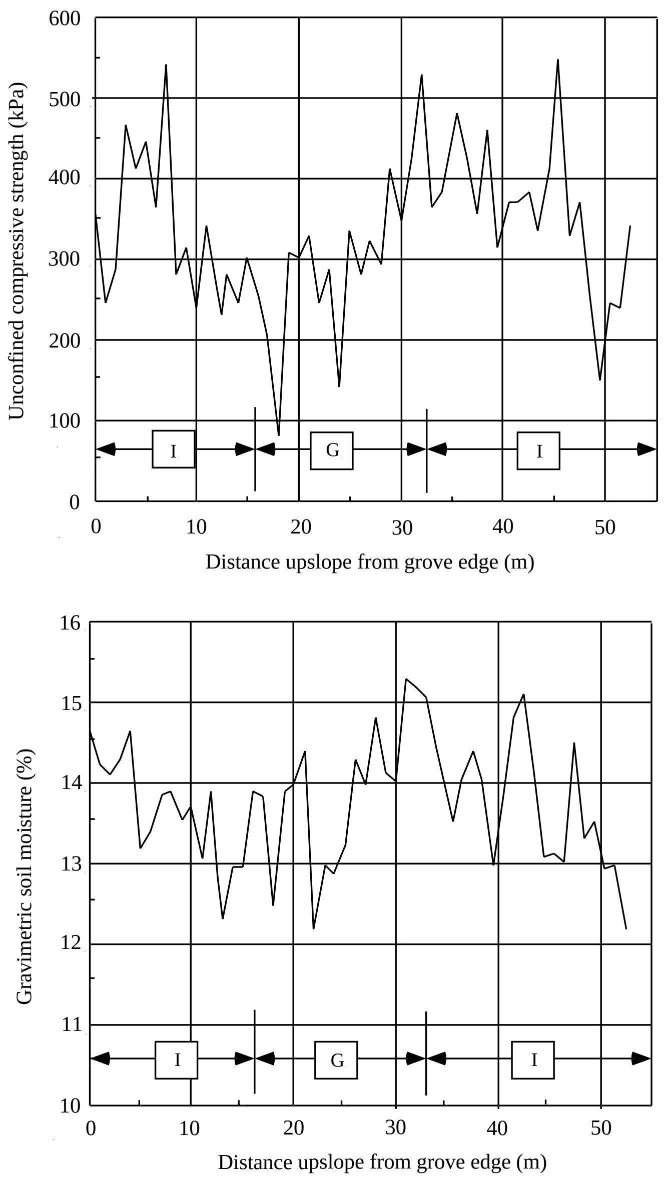

Figure 4. Transects of soil compressive strength (upper) and gravimetric water content (lower) on Transect No. 3, which extends upslope for 53 m across an intergove–grove–intergrove cycle. Note the general trends for the values to rise and fall between extrema at the intergrove–grove boundaries.

in situ soil moisture levels reported earlier showed that the soils were increasingly dry close to the stem. In view of the large volumes of stemflow delivered to the tree base, and the efficient retention of the water in highly permeable soils there, these data can be taken to indicate that the soil water store had been depleted more by transpiration near the mulga (or had percolated deeper into the soil column) than by the grasses of the open intergrove.

Table 3. *Results of analyses of trends in gravimetric soil moisture content (smc, %) and unconfined compressive strength (ucs, in kPa) regressed against distance upslope (m) from the base of Menindee transects 1–3*

	Location within transect	Soil parameter	*a*	*b*	Probability
Transect 1	Lower intergrove	ucs	390·9	−7·16	< 0·0001*
		smc	14·5	−0·09	< 0·0001*
	Grove	ucs	89·6	9·19	0·0016*
		smc	11·5	0·099	0·0003*
	Upper intergrove	ucs	819·1	−10·50	0·01*
		smc	16·9	−0·074	0·028*
Transect 2	Lower intergrove	ucs	328·9	12·1	0·002*
		smc	14·1	−0·07	0·047*
	Grove	ucs	560·0	−5·46	0·009*
		smc	13·3	0·014	0·52
	Upper intergrove	ucs	319·2	2·02	0·35
		smc	14·5	−0·02	0·078
Transect 3	Lower intergrove	ucs	562·1	−4·41	0·43
		smc	13·1	−0·11	0·034*
	Grove	ucs	829·3	−12·0	0·022*
		smc	12·1	0·03	0·40
	Upper intergrove	ucs	322·8	4·2	0·002*
		smc	13·3	0·02	0·012*

All regressions are least-squares linear models of the form $y = a + bx$. A separate regression model is listed for each vegetation component (intergrove or grove).
*Indicates significance at $\alpha = 0{\cdot}05$.

Evidence of upslope migration of the mulga grove pattern

The comparison of 1974 and 1998 aerial photographs showed no significant changes in the location of groves. In a few places, perhaps related to the death of trees, there were minor shifts in the boundary over short distances. However, no consistent movement was detected. Numerical models of tree groves based upon calibrated 'runoff–runon' conceptions (e.g. Klausmeier, 1999) require continual upslope progression of the whole pattern at rates of about 0·5 m a^{-1}, which equates to about 12 m displacement during the 24-year interval between the 1974 and 1998 images. This is about 50% of the width of an intergrove or grove, and such displacement would certainly have been resolvable in the photographs.

The 1974 photographs were monochrome, whilst the 1998 photographs were in colour, and this contributed to some differences in image tone. Bearing this in mind, there was a suggestion that tree density in some locations was lower in 1998 than in 1974.

Discussion

Grass cover in the study area was undoubtedly greater than in years of more normal rainfall. Likewise, the soil moisture levels reported here probably exceed the usual levels for the month of June (early winter), when observations were made.

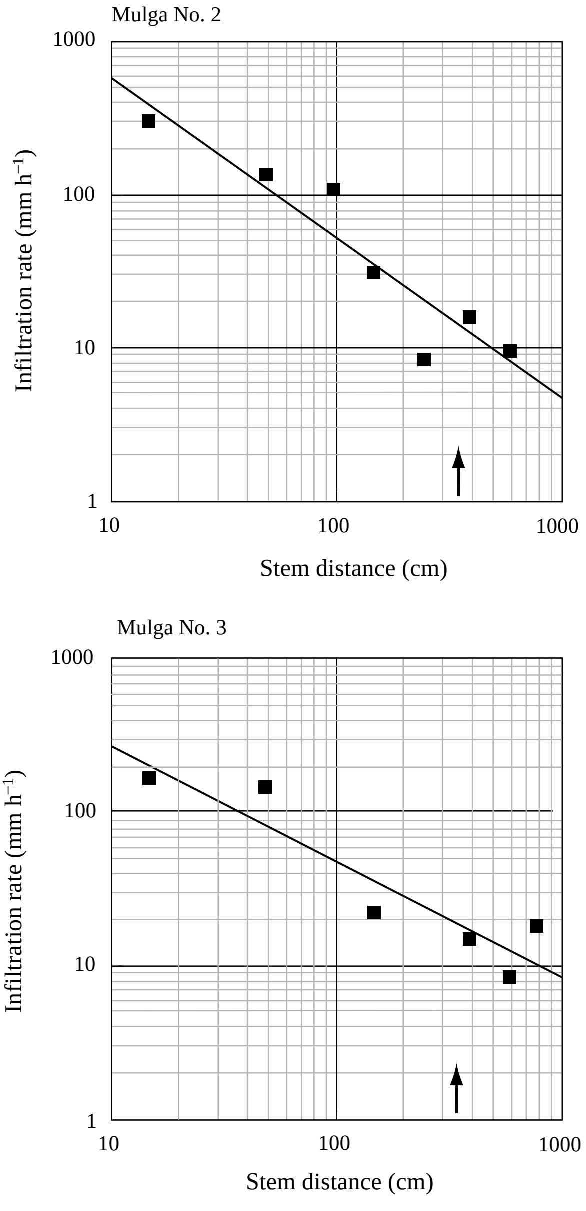

Figure 5. Radial infiltration rate transects around representative mulga trees—mulga No. 2 (upper) and No. 3 (lower). Least-squares power functions are indicated on each graph, and an arrow marks the outer limit of the tree canopy along the line of the transect. The regression equations are reported in Table 3.

These unusual conditions nevertheless allow some interesting conclusions to be drawn.

The substantial point-to-point variations in water content along the various transects (Fig. 2) are taken to reflect the distribution of grass tussocks, preferred flow pathways adopted by surface runoff, the mantling of intergrove surfaces by gravel

Table 4. *Details of canopy diameter on the axis of the radial infiltration transects around four grove mulga trees, together with the fitted power-function models linking infiltration rate and stem distance. Power functions take the form* $f = a\,d_s^b$, *where* f *is infiltration rate in* mm h^{-1} *and* d_s *is stem distance in cm*

Mulga stem radial transect number	Canopy radius (m) on transect axis	*a*	*b*	Probability
1	2·3	6677	−1.64	0·019
2	3·7	6186	−1·04	0·002
3	3·3	1437	−0·75	0·008
4	2·3	645	−0·51	0·082

veneers observed in some locations, the varying influence of rain interception on plant canopies, and the damming of flow by litter and fallen branches as it passes into the groves. It is emphasized that only the uppermost soil materials were sampled, so that total water stored in the soil column remains unknown. Nevertheless, patterns of surface soil wetness are taken to provide a useful indication of the relative volume of infiltration within various zones of the landscape. Profiles of soil moisture through the full rooting depth of the mulga tress would, however, be desirable in any subsequent investigation.

Despite the high level of variability in soil moisture, there was a clear trend for grove soils to become drier downslope. This suggests that despite the very wet antecedent months, insufficient runon water reached the lower grove soils to wet them to the same degree as soils nearer the upslope grove margin, which first intercept the runon from upslope. The alternative hypothesis is that the exceptional volumes of runon that seem likely to have arisen in the wet antecedent months would have been sufficient to wet-up all of the grove soils, which had subsequently dried out differentially. However, little difference in evaporative loss would be expected within the groves, and no evident differences in tree density or size were noted between upslope and downslope parts of the groves that could account for the systematic downslope drying trend. Thus, differential water loss (including transpirational water use) since the soils were wetted seems unlikely to be the explanation, and the pattern, therefore, appears to reflect uneven cumulative wetting during the runoff events that delivered water from the intergroves to the groves. In other words, even the exceptionally wet antecedent months were insufficient to deliver as much water to the lower parts of groves as to their upslope edges. This clearly suggests that surface runoff is very strongly absorbed within the grove soils, and particularly in those soils nearest to the intergrove upslope. Whilst runon thus appears to deliver most water to the upslope parts of the grove, tree density and size show no evident change through the grove. This same observation was reported by Slatyer (1965) in the reporting of some conference discussion appended to his paper. Consequently, the mulga trees in the lower part of a grove are not sustained by runon to the same extent as trees upslope are, and in view of this the grove hydrology is not uniform internally. If this is the case, then the ‘runoff–runon’ mechanism may only apply to the upper parts of the mulga groves. However, since trees evidently survive equally well in lower grove positions, the additional runon water available toward the top of the grove may not be essential for the mulga. This argument, developed more fully elsewhere (Dunkerley & Brown, submitted), raises the likelihood that factors other than the supply of soil moisture may regulate grove form. Interestingly, careful accounting of the water balance of banded vegetation has also suggested results not completely in accord with the mechanistic, ‘runoff–runon’ conception. For example, Seghieri & Galle (1999) performed a multi-year experiment on banded vegetation in Niger, and found that runon water was not essential to the life cycle of shrubs in parts of the grove. Instead, there was excess water available, and this escaped to deep drainage and was lost to the plants.

In a similar way to that just noted from the mulga groves, the tendency for intergrove soils to be driest at the upslope edge and become wetter downslope is consistent with both the lower infiltration rates found for intergrove soils, and with the consequent shedding of runoff water toward the lower intergrove. Furthermore, this pattern is consistent with the common observation that runoff forms ponds in the lowermost intergrove, from where it trickles into the following grove. The ponding represents a delay in the movement of the surface runoff, so providing opportunity time for infiltration that to some extent offsets the low infiltration rates exhibited by intergrove soils. Thus, whilst soil moisture levels in the present results peaked at the upslope edges of groves, soil wetness a few metres upslope into the intergrove (where ponds would have provided the water source) was comparable with that a similar distance downslope within the grove, where runon water was absorbed.

This raises the question of why the upslope grove margin is located in the middle of the belt of wettest soils in the landscape—the lowermost intergrove and the adjacent uppermost grove. Certainly, if the soil moisture patterns reported here are representative of the trends normally present at this site after rain, there is no difference in wetness in the lower intergrove and upper grove. Only surface soil wetness is reported here, but it seems reasonable to infer that ponding in the lower intergrove would feed some water into the subsoil, since though infiltration rates are lower than those near a mulga stem within the grove, the ponding would sustain a saturated soil surface (and a downward water flux) for a longer time. Furthermore, the soil compressive strength data (an example of which is contained in Fig. 3) show that on two of the three transects, the relatively moist surface soils of the lower intergroves and upper groves are also the weakest (200–400 kPa), the drier soils in upper intergrove or lower grove exhibiting greater strength (350–500 kPa). Values of ucs >2000 kPa are required before there is inhibition of the root development of crop and pasture species (Taylor *et al.*, 1966; Blanchar *et al.*, 1978). Whilst there are no relevant data on the growth of mulga root systems, it seems probable that these soils are not so mechanically strong as to pose a difficulty for the establishment of young trees from seed. The measured shear strengths are markedly lower than those reported from a banded chenopod shrubland in western New South Wales, Australia, where lower intergroves showed extremely hard soils with compressive strengths of up to 4000 kPa (Dunkerley & Brown, 1999). Such hard soils would offer great resistance to splash or flow entrainment, and perhaps to plant germination.

The ways in which mulga might colonize the lower intergrove are relevant here. Seed lodgment may be curtailed by the ephemeral ponding that arises in the lower intergroves, with seeds lost by floating downslope, or seeds may be consumed by termites, whose nests are concentrated in the intergroves. It is conceivable that root development is also diminished in very hard soils, but additional observations would be required to test these speculations. Consequently, from the present data, the factor responsible for setting the location of intergrove–grove boundaries remains unclear. Intergroves in the study area are considerably wider than groves in many cases, and the conventional view of this is that the groves become viable only when there is a sufficiently large intergrove to shed surface runoff into the grove (e.g. White, 1970). This argument seems less secure in the light of the data presented here. Whilst uppermost intergrove soils are indeed dry because they forfeit much of the arriving rain as surface runoff, the lower intergrove soils are as wet as upper grove soils. Furthermore, lower grove soils are also relatively dry, having about the same water content as upper intergrove soils. The mulga growing in lower grove locations, whilst perhaps deriving some water from upslope runoff, must derive a larger fraction of the required moisture by efficient stemflow funnelling into highly porous soils around the tree base, and thence into the root zone. The additional water derived from runon seems likely to amount to a small part of the total required to support the tree. The drier soils recorded around the isolated mulga tree in results presented earlier are consistent with the arriving water having passed into the deeper soil layers, leaving the surface relatively dry in comparison with interspace sites. Again it is emphasized that only surface soil wetness data were available in the present study, and a full tally of available water in the whole soil column might require modification of the interpretation offered.

A possible interpretation of the location of intergrove–grove boundaries in the part of the landscape having the wettest soils at the time of observation is that the boundary position is set under drier conditions, when landscape position does more strongly affect the conditions for plant growth. That is, perhaps when intergroves are less vegetated and runoff escapes from them more freely, the greater litter abundance and more porous soils of the groves create a much more marked difference in the availability of soil water between intergrove and grove. However, intergrove soils may shed nutrients as well as runoff water, so that in terms of seedling survival as well as soil water availability, intergroves may be relatively hostile environments. Additional data will be required to investigate these hypotheses. Nonetheless, the moisture content data presented here do not accord readily with the 'runoff–runon' view that suggests that the grove pattern is an adaptation to water scarcity, and a means of providing plants within the grove with the water required for survival. This suggests that whilst this is a superficially appealing hypothesis, given the pattern of lightly vegetated intergroves and contrasting wooded groves, it may not be the correct explanation. Additional work on the hydrology and ecology of this landscape will be required in order to develop a revised interpretation.

Some land management implications

It is possible that critical differences between intergrove and grove hydrology may be undergoing slow degradation as a result of the human use of this landscape. A possible decline in tree density between 1974 and 1998 was noted from the aerial photographs. Whilst working in the study area, the writer observed that extensive commercial mulga firewood gathering (the timber being for sale in the urban centre of Alice Springs) is carried out there, and it is possible that this is having a cumulative impact on the condition of the mulga groves. The additional effect of modern cattle grazing may also be a contributing factor. When wet, the soils are deeply pitted by the hoof stress imposed by cattle, and the numerous depressions so created would act to detain runoff within the intergove, so depriving the mulga groves of a fraction of the runoff they would otherwise receive. Likewise, the removal of dead mulga timber from the groves removes one source of frictional retardation of the surface runoff, diminishes the recycling of organic matter. The loss of timber may have an impact on termite populations, and so on soil porosity. A programme of data collection spanning many years would be necessary to resolve these issues.

Origin of the radial infiltration trends in mulga groves

Within the upper 20 cm of the soil, radiating root systems spread widely from the mulga, a reach of 13 m laterally having been reported for a 5 m tall tree (Anderson &

Hodgkinson, 1997). Therefore, a radially declining abundance of root-related macropores may provide part of the explanation for the gradational trends in infiltration rate, which show no jump at the overhead canopy edge. From a site in Queensland, root distribution measurements have indicated that 45% of mulga roots having a diameter > 5 mm lie within 1 m of the tree bole, with only 13% of such roots found > 4 m from the bole (Pressland, 1978). No data appear to be available on whether there is an equivalent spread of roots from mulga near the upslope grove boundary into the lower intergrove, or from trees downslope into the upper intergrove.

The controls on intergrove and grove dimensions

Despite the various limitations of the present data, it has been shown that the simple runoff–runon view of the hydrologic operation of these intergrove–grove systems does not adequately reflect the more complex controls on water redistribution. In particular, groves are not uniformly and strongly absorbing throughout. Rather, true interspace soils within the groves show about the same infiltration rates as intergrove soils, and it is the radially distributed zones of enhanced infiltration distributed in a patchy way coincident with the distribution of stems that really characterizes the grove soils. The same conclusion was drawn in the very different context of the groves within mosaic bluebush shrublands elsewhere in Australia (Dunkerley, 2000) so that there is evidence of this pattern being a more widespread one. Models of the development and operation of banded and groved landscapes (Thiéry, *et al.*, 1995; Klausmeier, 1999; Dunkerley, 1997) will, therefore, need to incorporate measures of this behaviour in order to represent more realistically the patchy soil hydraulics of these landscapes, which involve greater complexity than the commonly adopted view that envisages simple runoff and runon zones with sharply distinct soil hydraulic properties and soil moisture distributions.

Conclusions

Several findings emerge from this preliminary survey of water redistribution in central Australian mulga groves:

(1) Patterns of soil moisture are not consistent with the two-way partitioning of these landscapes into relatively impermeable intergroves and more permeable groves. Instead, each zone is a patchwork of soils having different infiltration capacities and soil moisture levels. It is emphasized that the soil moisture data presented earlier relate only to the upper 6 cm of the soil profile. Thus, the results do not reveal anything of the variation in the deeper soil moisture stores that might be accessed by the root systems of the mulga trees, and a fuller investigation of soil moisture through the full rooting depth seems warranted.

(2) Within the groves, infiltration rates are highest within the immediate vicinity of the mulga stems. However, enhanced infiltration rates persist well beyond the canopy limits and into any open space beyond. This is the same behaviour as reported from chenopod shrublands elsewhere in Australia.

(3) The downslope decline in the abundance of soil moisture mapped within groves cannot readily be reconciled with the idea that mulga groves are an adaptation to water shortage, and have a structure which serves to concentrate

runon water (sourced from the intergroves) in such a way as to sustain the grove.

(4) Similarly, the position of the intergrove–grove boundary, which was shown to sit in the middle of the wettest belt of soils in the landscape, is not readily explicable in terms of available soil moisture. This suggests that other factors might be involved in setting the location of these boundaries. Nutrient availability, or soil physical properties (such as bulk density or compressive strength) might be involved, through their effect on root growth and seedling development.

(5) There is no evidence of systematic upslope pattern migration judged over a 24-year period. This contrasts with the predictions of behaviour derived from numerical models of the operation of 'runoff–runon' systems. Taken together with the issues raised by the soil moisture data, these results suggest that much remains to be learned about the development and continued operation of mulga groves in the Australian landscape.

I thank Jamie Evans of Hamilton Downs pastoral property, Northern Territory, for kindly allowing the fieldwork to be carried out. Thanks also to Susan Dunkerley for her assistance in the field and to two anonymous reviewers for helpful suggestions. The work was supported by funding from the Australian Research Council. The aerial photograph of Fig. 1 is © Commonwealth of Australia, provided by AUSLIG, the Australian National Mapping Agency. It is reproduced by permission of the General Manager, Australian Surveying and Land Information Group, Department of Industry, Science and Resources, Canberra, Australian Capital Territory. Apart from any use as permitted under the Copyright Act 1968, no part maybe reproduced by any process without prior written permission from AUSLIG.

References

Anderson, V.J. & Hodgkinson, K.C. (1997). Grass-mediated capture of resource flows and the maintenance of banded mulga in a semi-arid woodland. *Australian Journal of Botany*, **45**: 331–342.

Blake, G.R. & Hartge, K.H. (1986). Bulk density. In: Klute, A. (Ed.), *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*, (2nd Edn), pp. 363–375. Madison, Wisconsin: American Society of Agronomy. 1188 pp.

Blanchar, R.W. Edmonds, C.R. & Bradford, J.M. (1978). Root growth in cores formed from fragipan and B2 horizons of Hobson soil. *Soil Science Society of America Journal*, **42**: 437–440.

Boyland, D.E. (1973). Vegetation of the mulga lands with special reference to south-western Queensland. *Tropical Grasslands*, **7**: 35–42.

Bromley, J., Brouwer, J., Barker, A.P., Gaze, S.R. & Valentin, C. (1997). The role of surface water redistribution in an area of patterned vegetation in a semi-arid environment, south-west Niger. *Journal of Hydrology*, **198**: 1–29.

Casenave, A. & Valentin, C. (1992). A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa. *Journal of Hydrology*, **130**: 231–249.

Cornet, A.P. Delhoume, J.P. & Montana, C. (1988). Dynamics of striped vegetation patterns and water balance in the Chihuahuan Desert. In: During, H.J., Werger, M.J.A. & Willems, H.J. (Eds), *Diversity and Pattern in Plant Communities*, pp. 221—231. The Hague: SPB Academic Publishing. 278 pp.

Dawson, N.M. & Ahern, C.R. (1973). Soils and landscapes of mulga lands with special reference to south western Queensland. *Tropical Grasslands*, **7**: 23–34.

Delta-T Devices Ltd. (1999). Theta probe soil moisture sensor. User manual, Delta-T Devices Ltd., 128 Low Road, Burwell, Cambridge United Kingdom, 22 pp.

Dunkerley, D.L. (1997). Banded vegetation: development under uniform rainfall from a simple cellular automaton model. *Plant Ecology*, **129**: 103–111.

Dunkerley, D.L. (2000). Hydrologic effects of dryland shrubs: defining the spatial extent of modified soil water uptake rates at an Australian desert site. *Journal of Arid Environments*, **45**: 159–172.

Dunkerley, D.L. & Brown, K.J. (1995). Runoff and runon areas in a patterned chenopod shrubland, arid western New South Wales, Australia: characteristics and origin. *Journal of Arid Environments*, **30**: 41–55.

Dunkerley, D.L. & Brown, K.J. (1999). Banded vegetation near Broken Hill, Australia: significance of surface roughness and soil physical properties. *Catena*, **37**: 75–88.

Dunkerley, D.L. & Brown, K.J. (submitted). Oblique vegetation banding in the Australian arid zone: implications for theories of pattern evolution and maintenance. *Journal of Arid Environments*, submitted.

Gee, G.W. & Bauder, J.W. (1986). Particle-size analysis. In: Klute, A. (Ed.), *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*, (2nd Edn), pp. 383–411. Madison, Wisconsin: American Society of Agronomy. 1188 pp.

Goodspeed, M.J. & Winkworth, R.E. (1978). Fate and effect of runoff—with particular reference to arid and semi-arid plain lands. In: Howes, K.M.W. (Ed.), *Studies of the Australian Arid Zone. III. Water in Rangelands*, pp. 53–63. CSIRO, Australia: Division of Land Resources Management. 255 pp. Proceedings of the Symposium held by the Rangelands Research Unit, Alice Springs Field Centre, 15–18 October 1974.

Klausmeier, C.A. (1999). Regular and irregular patterns in semiarid vegetation. *Science*, **284**: 1826–1828.

Low, W.A. (1978). The physical and biological features of Konoth Paddock in central Australia. Vol. 4. Melbourne: CSIRO Division of Land Resources Management. *Technical Paper*, 137 pp.

Mabbutt, J.A. & Fanning, P.C. (1987). Vegetation banding in arid Western Australia. *Journal of Arid Environments*, **12**: 41–59.

Pressland, A.J. (1973). Rainfall partitioning by an arid woodland (*Acacia aneura* F. Muell.) in south-western Queensland. *Australian Journal of Botany*, **21**: 235–245.

Pressland, A.J. (1976). Soil moisture redistribution as affected by throughfall and stemflow in an arid zone shrub community. *Australian Journal of Botany*, **24**: 641–649.

Pressland, A.J. (1978). Soil moisture distribution and evapotranspiration of a mulga (*Acacia aneura* F. Muell.) scrubland in south western Queensland. In: Howes, K.M.W. (Ed.), *Studies of the Australian Arid Zone. III. Water in Rangelands*, pp. 129–138. CSIRO, Australia: Division of Land Resources Management. 255 pp. Proceedings of the Symposium held by the Rangelands Research Unit, Alice Springs Field Centre, 15–18 October 1974.

Reynolds, W.D. (1993). Saturated hydraulic conductivity: field measurement. In: Carter M.R. (Ed.), *Soil Sampling and Methods of Analysis*, pp. 599–613. Boca Raton: Lewis, for Canadian Society of Soil Science. 823 pp.

Rhoades, J.D. (1982). Soluble salts. In: Page, A.L. (Ed.), *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, (2nd Edn), pp. 167–179. Madison, Wisconsin: American Society of Agronomy, 1159 pp.

Seghieri, J. & Galle, S. (1999). Run-on contribution to a Sahelian two-phase mosaic system: soil water regime and vegetation life cycles. *Acta Oecologica*, **20**: 209–217.

Slatyer, R.O. (1961). Methodology of a water balance study conducted on a desert woodland (*Acacia aneura* F. Muell.) community in central Australia. In: *Proceedings of the Madrid Symposium on Plant–Water Relationships in Arid and Semi-Arid Conditions*. UNESCO Arid Zone Research, Vol. 16, pp.15–26. UNESCO: Paris.

Slatyer, R.O. (1965). Measurements of precipitation interception by an arid zone plant community (*Acacia aneura* F. Muell). In: Eckardt, F.E. (Ed.), *Proceedings of the Montpellier Symposium on Methodology of Plant Eco-physiology*, UNESCO Arid Zone Research, Vol. 25, pp.181–192. Paris: UNESCO.

Taylor, H.M., Roberson, G.M. & Parker, J.J. (1966). Soil strength—root penetration relations for medium—to coarse-textured soil materials. *Soil Science*, **102**: 18–22.

Thiéry, J.M., d'Herbès, J.-M. & Valentin, C. (1995). A model simulating the genesis of banded vegetation patterns in Niger. *Journal of Ecology*, **83**: 497–507.

Tongway, D.J. & Ludwig, J.A. (1990). Vegetation and soil patterning in semi-arid mulga lands of eastern Australia. *Australian Journal of Ecology*, **15**: 23–34.

Valentin, C., d'Herbès, J.M. & Poesen, J. (1999). Soil and water components of banded vegetation patterns. *Catena*, **37**: 1–24.

White, L.P. (1970). *Brousse tigrée* patterns in southern Niger. *Journal of Ecology*, **58**: 549–553.