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Spatial organisation of landscapes and its function in semi-arid woodlands, Australia

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Abstract

The spatial organisation of three major landscape types within the semi-arid woodlands of eastern Australia was studied by a detailed analysis of gradient-oriented transects (gradsects). The aim was to characterise the spatial organisation of each landscape, and to account for that organisation in functional terms related to the differential concentration of scarce resources by identifiable processes. Terrain, vegetation and soils data were collected along each gradsect. Boundary analysis was used to identify the types of landscape units at a range of scales. Soil analyses were used to determine the degree of differential concentration of nutrients within these units, and to infer the role of fluvial and aeolian processes in maintaining them. All three major landscape systems were found to be highly organised systems with distinctive resource-rich units or patches separated by more open, resource-poor zones. At the largest scale, distinct groves of trees were separated by open intergroves. At smaller-scales, individual trees, large shrubs, clumps of shrubs, fallen logs and clumps of grasses constituted discrete patches dispersed across the landscape. Our soil analyses confirmed that these patches act as sinks by filtering and concentrating nutrients lost from source areas (*e.g.*, intergroves). We suggest that fluvial runoff-runon and aeolian saltation-deposition are the physical processes involved in these concentration effects, and in building and maintaining patches; biological activities also maintain patches. This organisation of patches as dispersed resource filters (at different scales) has the overall function of conserving limited resources within semi-arid landscape systems. Understanding the role of landscape patchiness in conserving scarce resources has important implications for managing these landscapes for sustainable land use, and for the rehabilitation of landscapes already degraded.

Introduction

Landscapes within the semi-arid woodlands of eastern Australia, covering some 500,000 km^2 (Fig. 1), first appear on casual observation as a rather haphazard organisation of vegetation, soil and terrain associations. However, on closer inspection we have found one of these associations to have a high degree of spatial organisation and integration (Tongway and Ludwig 1990). Those areas of woodland dominated by mulga (*Acacia aneura* F. Muell. ex Benth.) are organised into topographic sequences of alternating mulga groves and intergroves. This pattern of organisation is a widespread feature on subdued stony ridges and slopes with reddish clay loam soils, locally known as hard red earths (Walker 1991).

However, as described by Walker, the semi-arid woodlands also contain other major landscape systems, including terrain-soil complexes described as

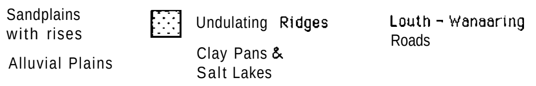

Fig. 1. The semi-arid woodlands of eastern Australia showing the location of the 'Avondale', 'Janina' and 'Lake Mere' study sites. The distribution and description of the semi-arid woodlands follows that in Harrington et *al.* (1984). The distribution and description of landforms within the study area follow the Land Systems of Walker (1991).

undulating sandplains and sandplains with dune rises. In this study, we address three basic questions: (1) are these sandplain landscapes as highly organised as mulga grove-intergrove landscapes, (2) what is the evidence to infer the landscape processes which maintain this structural integrity and (3) what is the function of this organisation?

The organisation of mulga woodlands into groves and intergrove is ascribed to runoff/runon processes, both in eastern Australia (Tongway and Ludwig 1990; Greene 1992) and central Australia (Perry 1970; Slatyer 1961). These same processes are used to explain similar landscape organisations in the Serengeti of East Africa (Belsky 1989) and the Chihuahuan Desert of Mexico (Cornet et al. 1992). In arid and semi-arid environments runoff/runon processes serve to concentrate scarce water and nutrient resources from source areas into sinks (Noy Meir 1973), for example, from intergroves into mulga groves. Our preliminary evidence for this concentration effect is that mulga grove soils have significantly higher levels of organic carbon and nitrogen than intergrove soils (Tongway and Ludwig 1990). In this study we provide additional evidence for this concentration effect by more intensively sampling soils in mulga grove-intergrove landscapes and in spatially organised units within sandplain landscapes.

We also have some evidence to suggest that these resource concentration processes also operate at scales smaller than groves-intergroves within semi-arid landscapes (Tongway et al. 1989). Fallen mulga trees accumulate fluvial and aeolian materials to form log mounds that have soils with significantly higher levels of nutrients and rates of water infiltration than soils adjacent to these log mounds. These same processes and accumulation effects operate for shrub mounds in the semi-arid chenopod shrublands of Western Australia (Tongway 1994). Such log and shrub mounds are fine-scale landscape resource sinks on the order of 2 m^2 to 5 m^2. Semi-arid landscapes appear to be organised into source-sink structures at a range of scales. In this study we provide evidence for accumulation effects at scales ranging from tree (≈ 100 m^2) to tree canopies (≈ 10 m^2) to shrub canopies and log mounds (≈ 5 m^2), and even down to individual grass tussocks (≈ 0.5 m^2). We hypothesise that all these different landscape sinks are spatially organised, connected and maintained by fluvial and aeolian landscape processes.

Earlier studies on the vegetation and soils of mulga woodlands in eastern Australia (Harrington

the transect is along a topographic gradient which should facilitate the recognition of different landscape units (*e.g.*, groves). This general method has been named the "gradsect" approach (Gillison and Brewer 1985). Site transects varied in length from 500 m at Lake Mere and Janina to 300 m at Avondale. Transect length was dictated by the longest landscape scale at each site.

Soil surface levels were measured along the transects at one metre intervals with a high-precision level-surveying instrument. Elevations were observed relative to a fixed benchmark positioned at the low end of the gradsect. Vegetation and soil surface attributes were observed in contiguous one-metre-square quadrats along each transect. The vegetation and soil surface attributes observed are known to be sensitive indicators of the condition (health) of arid and semi-arid landscapes (Ludwig and Tongway 1992, Tongway and Smith 1989). Perennial plant cover, by species, as a percentage of ground cover, was visually estimated using a quadrat with painted markings to aid in cover estimations. For the summary tables, species were classified into life forms.

A number of soil surface features were observed in the field. Surface crusts, when present, were classed into 8 categories based on brokenness and slaking performance; class 1 being most stable; class 8 least stable. Cryptogam cover was classified from 1 for nil to 4 for cover > 50%. Surface stoniness was categorised from 1 for stone cover > 50% to 4 for nil). The higher the class category, the greater the severity of the feature in terms of runoff/erosion potential. Also observed in the field were surface soil texture and pH; textures were assigned to a class from 1 to 18 based on increasing clay content.

Data Analysis

Gradsect data were subjected to boundary analysis, which identifies discontinuities along transects, that is, the location of landscape units (Ludwig and Cornelius 1987). The procedure is: (1) starting at one end of the gradsect, bracket the vegetation data for a set of contiguous quadrats into a 'window' of preassigned width, as for calculating moving averages; (2) split this window of spatially contiguous data into two equal groups; (3) average the data for each variate, that is, species cover, within each group; (4) compute a dissimilarity index (*e.g.*, Euclidean distance; Ludwig and Reynolds 1988) between these two groups; (5) move this split-window one position further along the gradsect and compute another dissimilarity; and (6) after moving the split-window along each position to the other end of the gradsect of data, with a dissimilarity computed for each window, plot the dissimilarities (distances at mid-point window positions) against gradsect position. The location of a boundary (landscape discontinuity) is represented by a peak in the plot of computed dissimilarities against gradsect distances.

Landscape units at different scales are detected by using different window widths. A wide window (*e.g.*, 100 quadrats) smoothes the data and identifies coarse-scale landscape units (*e.g.*, tree groves). A narrow window (*e.g.*, 10 quadrats) detects small or fine-scale landscape units (*e.g.*, grass clumps). Boundary analysis was first used with a window width of 100 to identify and located coarse-scale landscape zone.

The interpretation of environmental differences between coarse-scale landscape zones (*e.g.*, groves and intergroves) were investigated by using standard statistical tests. Significant differences in observed soil surface properties between the different landscape zones infer which landscape processes may be important in shaping the organisation of units within the landscape.

Soil sampling at depth was undertaken after completing the boundary analysis to determine whether certain landscape units are acting as resource sinks by accumulating nutrients. The coarse-scale landscape zones were sampled by collecting soil samples at random within each zones at depth intervals of 0–1, 1–3, 3–5, 5–10, 10–25 and 25–50 cm. For the finer-scale landscape units, such as log-mounds, grass clumps, shrub-mounds and tree canopies, triplicate soil samples were collected at the above depths both within and outside these units.

Soil samples were returned to the laboratory and analysed for pH and electrical conductivity

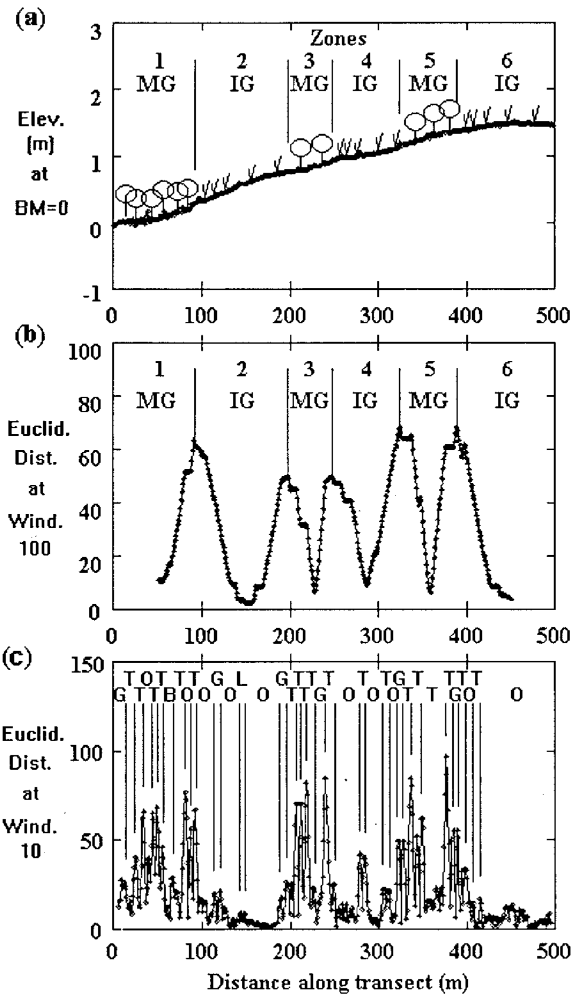

Fig. 2. Lake Mere gradsect: (a) Elevations along 500 m. (b) boundaries between six landscape zones defined by using a window width of 100 m; three mulga groves (MG) are separated by three open-grass intergroves (IG). (c) Small-scale patches defined by using a window width of 10 m; mulga trees (T), poplar box trees (B) and log mounds (L) are separated by open areas (O) and clumps of grasses (G).

(Loveday 1974), organic nitrogen (Twine and Williams 1967), potentially available nitrogen (Gianello and Bremmer 1986), available phosphorus (Colwell 1965) and organic carbon (Colwell 1969). These analyses were previously useful in discriminating zones of differing nutrient availability in related soil types (Tongway and Ludwig 1990).

Results

Undulating Stony Ridges and Slopes

Coarse-scale boundary analysis of the Lake Mere gradsect data, using a window width of 100 m, resulted in the identification of six landscape zones forming a topographic-sequence down from the top of a ridge (Fig. 2a,b). This topographic-sequence is repetitive, with three very similar zones (1, 3 and 5) alternating with the other three zones (2, 4 and 6). Zones 1, 3 and 5 are groves of trees located on slightly flattened 'ledges' on the slopes and at the bottom of the transect (Fig. 2a). These groves are characterised by a high cover (50–70%) of trees (at this site, mulga, *Acacia anuera* F. Muell. ex Benth.), and perennial grasses (16–23%) (Table 2a). Zones 2, 4 and 6 are open intergroves, with a relatively low cover of trees and shrubs (< 5%) and grasses (9–14%).

The condition of the soil crust, in terms of stability, was rated the most stable in mulga zones 1 and 5 (Table 2b; at this site only, low ratings indicate higher stability). The other zones did not differ significantly except zone 6 (located on the ridge), which rated the least stable. Zones 1 and 5 also had the lowest ratings for stone cover, others being significantly higher. Cryptogam cover was lowest in zone 1 where the mulga litter was deepest. Soil surface pH averaged 6.1 with a small range of variation. Thus, surface pH did not differ significantly over the six landscape zones on Lake Mere and, for simplicity, is omitted from Table 2b. Soil surface texture class was consistently a fine sandy clay loam over the entire Lake Mere gradsect and thus, for simplicity, these data are also omitted from Table 2b.

Soil samples collected within and between mulga groves on Lake Mere document a significant concentration of potentially available nitrogen (AN) in the surface soil layers of the mulga groves (Fig. 3a). There were no significant differences between the grove and intergrove soils collected below 10 cm. As expected, soil organic carbon (OC) had the same concentration effect as AN, with 2% OC in the groves and < 1% OC in the intergroves near the

Table 2. (a) Ground cover (% ± S.E.) of plant life forms and (b) soil surface characteristics (means ± S.E.) in six landscape zones delineated along a transect on Lake Mere.

	Landscape zones					
	1	2	3	4	5	6
(a) Plant Life Form						
Trees	68.5 ± 3.7	1.6 ± 0.6	50.0 ± 6.4	4.1 ± 1.6	60.4 ± 5.5	2.4 ± 1.0
Shrubs	0.6 ± 0.4	.04 ± .04	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Sub-shrubs	0.1 ± .06	0.1 ± .02	0.0 ± 0.0	.02 ± .01	.03 ± .02	.06 ± .02
Perennial Grasses	23.4 ± 1.7	8.8 ± 0.8	16.7 ± 1.9	13.7 ± 1.3	15.4 ± 1.4	9.8 ± 0.8
Perennial Forbs	2.7 ± 0.5	0.0 ± 0.0	2.2 ± 0.7	0.0 ± 0.0	1.4 ± 0.6	0.0 ± 0.0
(b) Soil Surface[1]						
Crust Stability[2]	3.5^a ± .06	4.5^b ± .08	4.2^b ± .14	4.2^b ± .10	3.7^a ± .10	5.0^c ± .05
Cryptogam Cover[3]	2.3^a ± .11	2.7^b ± .06	2.7^b ± .14	3.0^b ± .07	3.1^b ± .12	3.0^b ± .07
Stone Cover[3]	1.1^a ± .04	2.2^d ± .05	1.5^b ± .07	1.7^{bc} ± .07	1.1^a ± .04	1.9^c ± .05

[1] For each soil surface characteristic, means for zones with different superscript letters are significantly different ($p < 0.05$), based on Tukey's honestly significant difference test.

[2] For the Lake Mere site only, higher values for crust stability indicate lower ratings of soil surface stability.

[3] Higher ratings indicate greater cryptogam and stone cover on the soil surface.

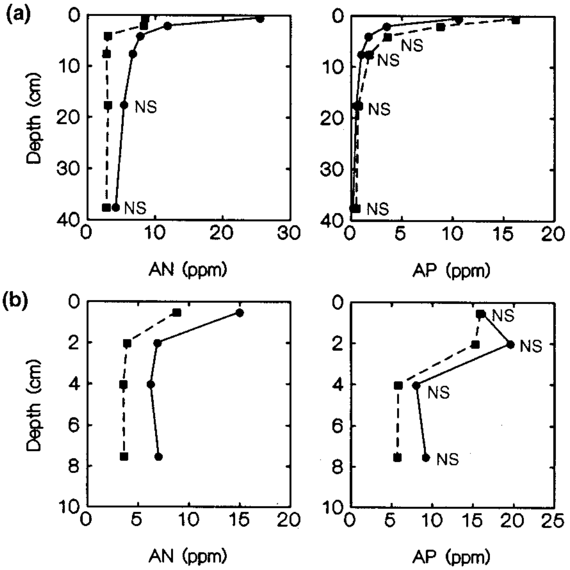

Fig. 3. Undulating stony ridges and slopes – the Lake Mere site: trends in available nitrogen (AN) and available phosphorus (AP) with profile depth for soil samples collected: (a) within mulga groves (solid line) and intergroves (dashed line) and (b) within mulga log mounds (solid line) and between mounds (dashed line). NS = non-significant differences ($p > 0.05$) in the means at this depth.

surface, and with no significant differences in soils collected below 10 cm; for simplicity, these results for OC are not presented in Fig. 3a. Available phosphorus (AP) was opposite to AN, and OC, with the grove near-surface soil profile layers having significantly less AP than the intergrove soil layers above 10 cm. Soil pH's were around 6.0 near the surface for both the grove and intergrove soils and become slightly more acidic with depth (5.5 @ 50 cm), not being significantly different with depth, these results are not shown in Fig. 3a.

Soils collected down to 10 cm on mulga log mounds had significantly higher concentrations of AN than soils collected off these log mounds (Fig. 3b). AP concentrations did not significantly differ on versus off the log mounds sampled at Lake Mere.

Fine-scale boundary analysis of data from the Lake Mere gradsect (window width = 10) defined a number of smaller landscape units (Fig. 2c). These units were identifiable as clusters of, or single, mulga trees (T), individual poplar box trees (B), mulga log mounds (L) and areas of dense grass clumps (G) interspersed with open areas (O) of bare, stony surfaces and low densities of ephemeral grasses and forbs.

Undulating Sandplains

Coarse-scale boundary analysis of data (window width = 100) from the Janina gradsect delimited

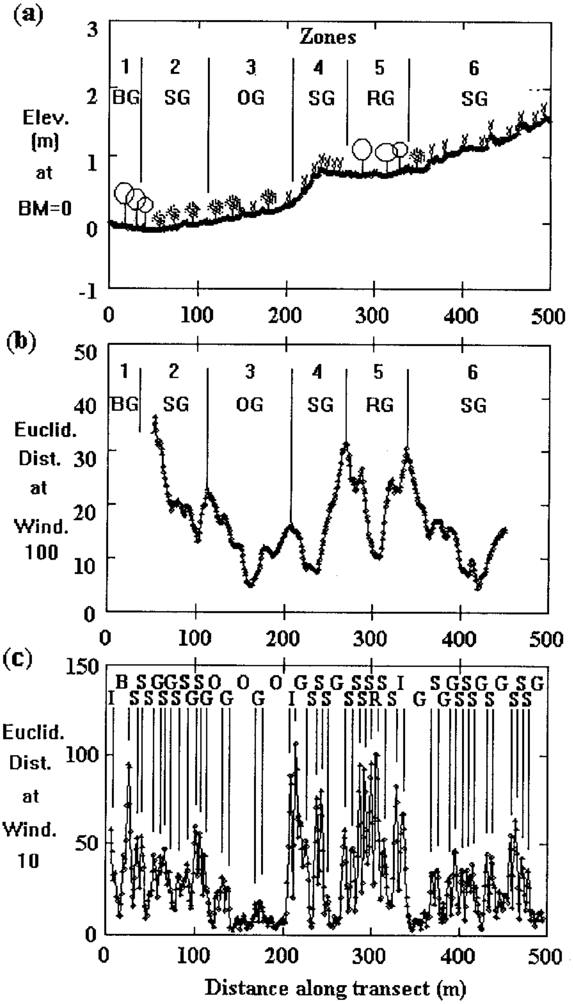

Fig. 4. Janina gradsect: (a) Elevations along 500 m. (b) Boundaries between six landscape zones defined by using a window width of 100 m; a poplar box grove (BG), lowest in the landscape, is separated from a ironwood-rosewood grove (RG) by shrubgrass (SG) and open-grass (OG) intergroves. (c) Small-scale patches defined by using a window width of 10 m; ironwood trees (I), poplar box trees (B), rosewood trees (R) and large shrubs (S) are separated by open areas (O) and clumps of grasses (G).

six landscape-scale elements or zones (Fig. 4a,b). Zone 1 is located in a depression at the bottom of the gradsect and is a grove of trees (Table 3a). This grove had dense overlapping canopies of poplar box (*Eucalyptus populnea* F. Muell.) and ironwood (*Acacia excelsa* Benth.). Zone 5 is a mixed-grove of rosewood (*Heterodendrum oleifolium* Desf.) and ironwood 'perched' on a flat area mid-slope along the gradsect. These two groves, along with zone 2, have a relatively high cover of shrubs, mostly punty (*Cassia eremophila* A. Cunn. ex Vogel) and emu bush (*Eremophila longifolia* (R.Br.) F. Muell.). Landscape zones 2, 3 and 4 are open shrub and grass areas occurring as intergrove slopes partially within and between two landscape depressions (Fig. 4a). Zone 6 occurs on the slopes above the rosewood grove depression and extends up to a low sandy ridge; it has no trees and a relatively high cover of perennial grasses (Table 3a).

The intergrove soil surface crusts were less stable than those within the groves (Table 3b) and intergrove surfaces also had a lower cover rating for cryptogams. Intergrove surface soil textures were also more sandy (*i.e.*, having less clay) than those within the groves. Surface soil pH was significantly lower in zone 4 and higher in zone 2, but the total range in surface pH across all six zones was only about 1 unit (5.6 to 6.7).

Soils collected with depth from within the woodland groves (poplar box and ironwood-rosewood) on the Janina sandplain landscape were also different from soils collected in the intergroves. Again, AN had a significantly higher concentration within in the top 10 cm of grove soils compared to that for intergrove soils (Fig. 5). Again, OC follows AN, with > 2% OC in the groves and < 1% OC in the intergroves near the surface, becoming non-significant below 10 cm; as AN reflects OC, the results for OC are not presented in Fig. 5. AP was only significantly elevated in the near surface soil layer for groves compared to intergroves. At the surface, pH was close to neutral (about 6.5) for both groves and intergroves, becoming slightly more acidic with depth (about 5.5) with no significant differences; these results are not shown in Fig. 5.

Boundary analysis of vegetation data from the Janina gradsect delimited a number of fine-scale landscape units (Fig. 4c). These units were identified as individual poplar box (B), ironwood (I) and rosewood (R) trees and many clumps of shrubs (S) and grasses (G) interspersed with a few open areas (O).

Table 3. (a) Ground cover (% ± S.E.) of plant life forms and (b) soil surface characteristics (means ± S.E.) in six landscape zones delineated along a transect on Janina.

	Landscape zones					
	1	2	3	4	5	6
(a) Plant Life Form						
Trees	109.0 ± 6.3	0.7 ± 0.4	0.0 ± 0.0	18.5 ± 4.6	17.4 ± 4.1	0.0 ± 0.0
Shrubs	55.7 ± 5.4	46.3 ± 4.0	5.1 ± 1.6	5.5 ± 1.9	49.7 ± 5.1	12.7 ± 1.8
Sub-shrubs	1.1 ± 0.3	1.6 ± 0.3	3.2 ± 0.5	2.5 ± 0.5	5.6 ± 0.9	2.2 ± 0.3
Perennial Grasses	7.0 ± 1.1	17.7 ± 1.1	7.3 ± 0.6	19.1 ± 1.9	15.8 ± 1.1	22.4 ± 1.2
Perennial Forbs	5.6 ± 1.2	6.9 ± 1.4	0.0 ± 0.0	0.3 ± 0.1	1.9 ± 0.5	0.1 ± 0.1
(b) Soil Surface[1]						
Crust Stability[2]	3.8^a ± .09	4.0^a ± .02	3.8^a ± .05	2.8^b ± .07	3.8^a ± .05	3.0^b ± .06
Cryptogam Cover[3]	1.4^c ± .10	2.9^a ± .07	2.0^b ± .02	1.9^b ± .08	2.9^a ± .06	1.9^b ± .05
pH	6.1^b ± .04	6.7^a ± .05	6.2^b ± .04	5.6^c ± .08	6.4^a ± .10	6.3^b ± .04
Textural Class[4]	17.1^a ± 0.3	17.7^a ± 0.4	12.8^b ± 0.2	9.3^c ± 0.4	18.9^a ± 0.4	12.2^b ± 0.3

[1] For each soil surface characteristic, means for zones with different superscript letters are significantly different ($p < 0.05$), based on Tukey's honestly significant difference test.

[2] Higher values for crust stability indicate higher ratings of soil surface stability.

[3] Higher ratings indicate greater cryptogam cover on the soil surface.

[4] Higher numbers equal greater clay content in surface soils.

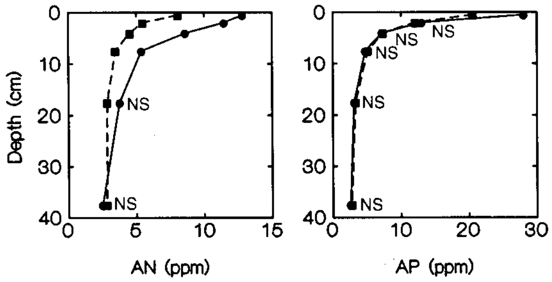

Fig. 5. Undulating sandplains – the Janina site: trends in available nitrogen (AN) and available phosphorus (AP) with profile depth for soil samples collected within box ironwood-rosewood groves (solid line) and within open intergroves (dashed line). NS = non-significant differences ($p > 0.05$) in the means at this depth.

Sandplains with Dune Rises

Coarse-scale analysis of the Avondale data distinguished seven landscape zones (Fig. 6a,b). Zones 1, 4 and 6 are characterised by high tree cover (Table 4a); zone 1 is a gidgee (*Acacia cambagei* R.T. Bak.) grove and zones 4 and 6 are rosewood groves. Zones 2 and 3 are shrub and grass dominated (by turpentine, *Eremophila sturtii* R. Br., and woollybutt, *Eragrostis eriopoda* Benth., respectively), whereas zones 5 and 7 are grasslands, being dominated solely by woollybutt. The gidgee and turpentine zones (1 and 2) are located low in the landscape (Fig. 6a), in what are locally referred to as swales. The rosewood zones (4 and 6) are located at the site of small depressions higher in the landscape. The woollybutt zones (5 and 7) are on the sides and top of the low (2 m) dune rise.

The zones located lower in the landscape had a higher crust stability than those on the dune rises except for grassy zone 6 (Table 4b). Cryptogam cover was lowest within the two rosewood groves (zones 4 and 6). The gidgee grove (zone 1) had a finer textural class (more clay), with the dune rise being sandiest. The Avondale site had no stony surface pavements; thus, these data are not presented in Table 4b.

Along the Avondale topographic-sequences, soils collected within groves of trees were again significantly higher in AN near the surface, but quickly became non-significant with depth (Fig. 7a). There were no significant differences in OC at any depths (values < 1%); for simplicity these data are not shown in Fig. 7a. However, AP was significantly higher within groves than between groves down to 20 cm. Soils from both groves and intergroves were

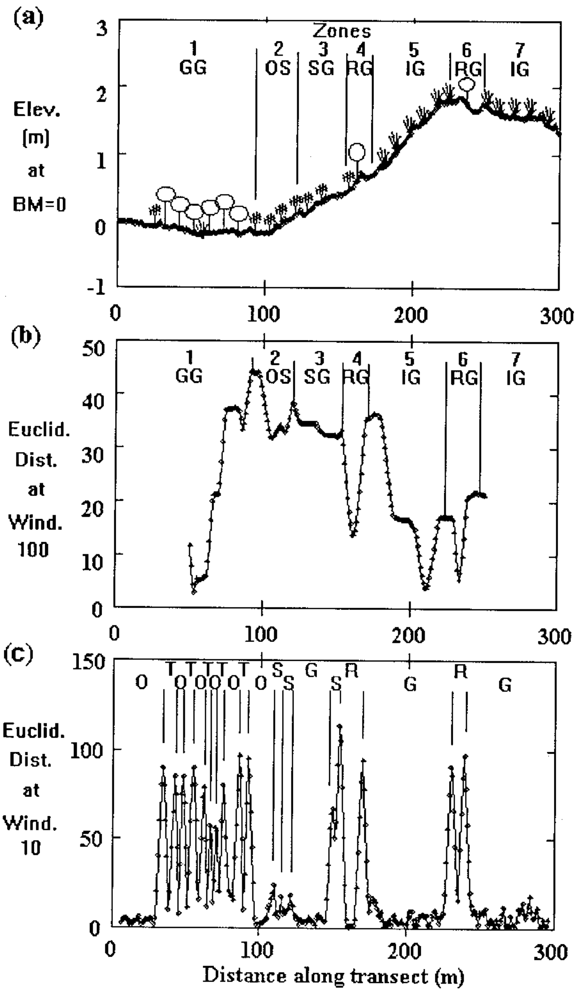

Fig. 6. Avondale gradsect: (a) Elevations along 300 m. (b) Boundaries between seven landscape zones defined by using a window width of 100 m; a gidgee grove (GG), lowest in the landscape, is separated from two rosewood groves (RG) by an open shrub zone (OS), a shrub-grass zone (SG) and two grassy intergroves (IG). (c) Small-scale patches defined by using a window width of 10 m; gidgee trees (T), rosewood trees (R) and large shrubs (S) are separated by open areas (O) and areas with grass clumps (G).

slightly acid near the surface (5.5), becoming more neutral with depth (6.5); being non-significant, these results are not shown in Fig. 7a.

A different distribution of patches is evident along the Avondale dune rise-swale gradsect (Fig. 6c). Woollybutt grass patches (G) are evenly dispersed between distinctive individual rosewood trees (R) across the intergrove dune rise (*e.g.*, zones 5 & 7; Fig. 6a). In the lowest areas (*e.g.*, zones 1 and 2), gidgee trees (T) and turpentine shrubs (S) are separated by bare open areas (O). Soils collected under individual shrub canopies and in the open areas between shrub canopies were not significantly different in AN at any depth (Fig. 7b), although statistically non-significant, AN (and OC) had higher measured values down to 5 cm. If sample sizes had been larger, statistically significant differences may have been found at near-surface depths.

As with shrubs, no significant differences were found in AN measured within soils collected under and between woollybutt grass tussocks down to 10 cm (Fig. 7c), although again AN (and OC) had higher means under the tussocks and more intensive sampling may have indicated statistical significance. The concentration of AP was relatively high in the top 2 cm (≈ 15–20 ppm) both under and between shrubs and grass tussocks (Fig. 7b,c). In these light-textured Avondale soils, pH values were very variable because these soils are weakly buffered; thus, pH results are not displayed in Fig. 7.

Discussion

Three different major landscape systems within the semi-arid woodlands of eastern Australia were found to be highly organised systems. Stony ridges and slopes, undulating sandplains and sandplains with low dune rises were all organised into distinctive units or patches separated by open spaces at a range of scales. At the largest scale, groves of trees were organised into repeating sequences with open intergroves. Groves were found on slightly flattened areas or in slight depressions along slopes of, or at the bottom of, the transects studied. Although the tree species differed, all three landscapes formed these grove-intergrove topographic sequences. This type of landscape organisation appears to be a distinctive characteristic in other arid and semi-arid regions of the world, *e.g.*, vegetation 'patches' in the Serengeti of East Africa (Belsky 1989) and vegetation 'stripes' in the Chihuahuan Desert of Mexico (Cornet *et al.* 1992; Montana 1992).

At smaller scales we found all three semi-arid landscape sites had other types of units or patches in a dispersed form of organisation. Individual

Table 4. (a) Ground cover (% ± S.E.) of plant life forms and (b) soil surface characteristics (means ± S.E.) in seven landscape zones delineated along a transect on Avondale.

	Landscape zones						
	1	2	3	4	5	6	7
(a) Plant Life Form							
Trees	32.8 ± 4.6	0.0 ± 0.0	0.3 ± 0.3	97.2 ± 1.9	0.2 ± 0.2	85.0 ± 9.3	0.0 ± 0.0
Shrubs	2.7 ± 0.8	6.3 ± 2.0	10.2 ± 4.8	0.9 ± 0.3	0.0 ± 0.0	1.0 ± 0.3	0.5 ± 0.5
Sub-shrubs	2.2 ± 0.2	1.4 ± 0.3	0.9 ± 0.2	0.1 ± .08	0.2 ± .06	.05 ± .05	0.5 ± .14
Perennial Grasses	0.2 ± .05	1.1 ± 0.6	13.8 ± 1.1	0.7 ± 0.4	23.2 ± 1.2	0.4 ± 0.3	29.9 ± 1.3
Perennial Forbs	.05 ± .03	.11 ± .11	.03 ± .03	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.5	0.0 ± 0.0
(b) Soil Surface[1]							
Crust Stability[2]	2.5^{a} ± .06	2.3^{ab} ± .14	2.2^{bc} ± .13	2.0^{bc} ± .01	1.8^{c} ± .07	1.1^{*} ± .00	2.3^{ab} ± .06
Cryptogam Cover[3]	1.8^{bc} ± .08	2.3^{a} ± .13	2.1^{ab} ± .14	1.0^{*} ± .00	1.5^{c} ± .09	1.0^{*} ± .00	1.9^{ab} ± .11
Textural Class[4]	13.7^{a} ± .19	9.7^{b} ± .65	6.5^{c} ± .33	10.2^{b} ± .51	5.8^{c} ± .20	5.0^{*} ± .00	5.0^{*} ± .00

[1] For each soil surface characteristic, means for zones with different superscripts (a > b > c) are significantly different ($p < 0.05$), based on Tukey's honestly significant difference test; * denotes means not tested due to lack of variance.

[2] Higher values for crust stability indicate higher ratings of soil surface stability.

[3] Higher ratings indicate greater cryptogam cover on the soil surface.

[4] Higher numbers equal greater clay content in surface soils.

trees, large shrubs and clumps of smaller shrubs were identifiable as distinctive patches within more open groves. Within the open intergroves, shrubs and fallen logs form distinctive soil mounds, clumps of grasses formed discrete soil hummocks and, at the smallest scale, individual grasses formed tussocks. Again, the species of tree, shrub, log or grass differed between the three sites, but the organisation of these smaller-scale patches as dispersed units separated by open areas was similar across the landscape (Figs. 2c, 4c, 6c).

Landscapes in the semi-arid woodlands of eastern Australia are organised into source-sink systems. Tree groves, be they mulga, rosewood, ironwood, gidgee or box dominated, are sinks rich in resources. Our soils data indicate that these sinks concentrate nitrogen and organic carbon, partly derived from upslope source areas (*i.e.*, from ridges, dune rises and slopes) and partly by in-situ cycling of nutrients. Although, for simplicity, our soils data was presented to contrast the mean differences between groves and intergroves (Figs. 3a, 5 and 7a), our data clearly indicate that, as might be expected, smaller mid-slope groves were not as enriched as larger groves situated in the lowest depressions or swales.

We suggest that both fluvial and aeolian erosional/depositional processes are involved in these resource concentration effects. In the semi-arid woodlands, fluvial runoff-runon processes dominate. This is especially evident when observing runoff after intense rainfall events in all these landscapes, although each landscape type has a different soil texture which strongly mediates runoff quantity and rate. However, aeolian or wind saltation/deposition processes also play a role in shaping these ancient landscapes, particularly in dry times and when willy-willies (convectional whirl-winds) are observed to transport dust and litter debris over considerable distances. Our field observations from experimental landscape manipulation studies also support the importance of both water and wind in the redistribution and concentration of limited resources (Tongway and Ludwig 1993).

Further, smaller-scale landscape patches; such as log-mounds and shrub-mounds also function as resource traps or sinks. Log-mounds and shrub-mounds significantly concentrate nutrients and have a high capacity for water intake compared to surrounding areas (Tongway *et al.* 1989; Greene and Tongway 1989). Such patches show a richness in biogenic nutrients, such as organic carbon and mineralisable nitrogen, indicating high levels of biological assimilation, accumulation and decom-

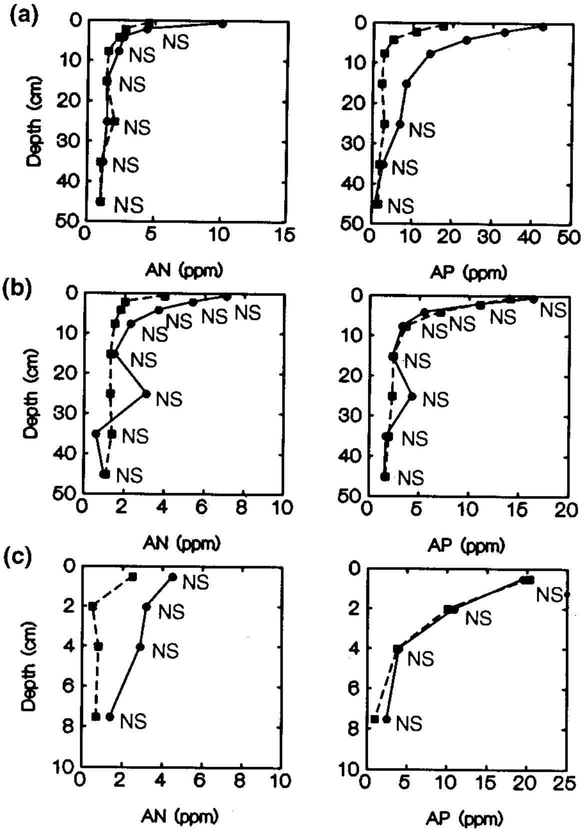

Fig. 7. Sandplains with dune rises – the Avondale site: trends in available nitrogen (AN) and available phosphorus (AP) with profile depth for soil samples collected: (a) within gidgee and rosewood groves (solid line) and within the grassy zones between these groves (dashed line), (b) under shrubs (solid line) and between shrubs (dashed line) and (c) within grass clumps (solid line) and between clumps (dashed line) – note that these samples were only collected down to the 5–10 cm depth as few grass roots extended below this depth. NS = non-significant differences ($p > 0.05$) in the means at this depth.

position. This indicates that these resource sinks internally process, turn-over and re-cycle nutrients, keeping nutrient levels high. Such landscape patches are described as 'fertile islands' (Garner and Steinberger 1989) or 'environmental resource patches' (Forman and Godron 1981). These smaller-scale landscape patches are rich habitats for all kinds of biological organisms, both vertebrates and invertebrates, such as ants and termites (Tongway *et al.* 1989; Whitford *et al.* 1992).

At the smallest scale, grass clumps, operating as individual tussocks or as clumps of tussocks, entrap windborne materials including litter fragments (*e.g.*, leaves, stems and influorescences) and soil particles to form accretion mounds. Larger mounds are formed when bridges of litter form between adjacent grass tussocks. During rainfall events with surface runoff, these bridges hold back water and transported materials. Within accretion mounds, grass roots, microfauna (*e.g.*, invertebrates) and microflora (*e.g.*, mycorrhizal fungi) play a vital biological role in creating a micro-habitat where soil aeration and infiltration are improved and soil nitrogen is maintained at higher concentrations (Charley 1972; Garner and Steinberger 1989).

In this study soils collected under woollybutt grass tussocks had higher means for nitrogen down to 10 cm than for soils between tussocks (Fig. 7c). However, these mean differences (≈ 2 ppm) were not statistically significant based on triplicate sampling; more intensive soil sampling may have indicated significant differences.

Landscape patches at all scales function to capture and retain scarce resources (water and nutrients) within the landscape system rather than having these carried right out of the system (*i.e.*, into a creek, river or lake). Even small-scale patches, such as grass clumps, serve as resource regulators, slowing down or capturing scarce resources as they flow and blow around the landscape. Each type and scale of patch has a finite capacity for this regulation, thus an organised 'community' of patches is most effective.

Because they act as natural landscape sieves or filters, rather than barriers, patches are relatively robust landscape features. Although small-scale patches are intrinsically less robust than large groves, they are none-the-less strongly maintained by biogenic processes. Patches allow massive water flows, occurring during intense rains, to filter through without damaging the patch. This feature of patches as filters is critically important when designing structures to rehabilitate landscapes by the construction of patches (*e.g.*, mulga branches in elongated piles across contours; Tongway and Ludwig 1993). These structures must emulate the natural sieve/filter properties of patches and the strong links occurring between patches within the landscape (Ludwig and Tongway 1992). The filtering capacity of patches and the total area of patch required to conserve all the water from rainfall events has been simulated with a landscape flow-filter model (Ludwig *et al.* 1994).

An understanding of landscape patchiness (at all scales) and the processes which maintain them, has very important implications for land management. In order to prevent semi-arid woodland landscapes from degrading, where degradation is defined as a significant decline in the response of landscapes to rainfall (Ludwig and Tongway 1992), a full range of large to small-scale patches should be maintained. One consequence of long-term intensive grazing of semi-arid landscapes is partial or complete loss of patchiness. Domestic and feral animals can destroy patches, particularly small-scale patches, by persistent grazing and trampling.

The loss of small-scale patches alters the dynamics of runoff/runon and erosion/deposition by increasing fetch, so that each runoff event involves a larger volume of water, transporting larger quantities of material. Mid-slope grove patches may not cope with these volumes and a greater proportion of material is transported out of the system. This is followed by a run-down in the quality of the soil within a degraded patch, or in the area where the patch once existed. Quality can drop below a critical threshold so that the area no longer functions as a habitat favourable for as many organisms.

In order to manage semi-arid landscapes for sustainable land use, it is necessary to understand how the spatial organisation of a landscape functions to conserve limited resources. Only an understanding of the dynamics of the landscape processes involved in maintaining patchiness and how processes are altered by degradation, and at what scales, can sustainable land use be achieved. This knowledge can be used to avoid irreversible degradation and, where some degradation has already occurred, to develop rehabilitation treatments.

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