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# Indicators of landscape function: comparing patchiness metrics using remotely-sensed data from rangelands

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**Abstract**

In arid and semi-arid rangeland regions, landscapes that trap and retain resources, such as rain water, soil particles, and organic matter, provide more favorable habitats for vegetation and fauna, and are considered more functional than landscapes that lose, or leak, these essential resources. The cover and arrangement of perennial vegetation patches is an important indicator of whether landscapes retain or leak resources. Patchiness attributes, as descriptors of resource retention potential in landscapes, can be obtained from remotely-sensed imagery, such as aerial videography and high-resolution satellites where this imagery has been classified into perennial vegetation patch and open interpatch pixels. In this paper, we compare four landscape patchiness metrics on their ability to indicate how well landscapes potentially function to retain resources. Landscape patch attributes (e.g. patch cover and spacing) and on-ground inspection of soil and vegetation attributes were used to rate and rank four sites relative to their potential to retain resources. A directional leakiness index (DLI) that is highly sensitive to patch cover, shape, and configuration correctly and adequately ranked sites in the same order as our field ratings. The lacunarity index also correctly ranked sites, but showed little separation amongst sites with reduced potential to retain resources. The weighted mean patch size (WMPS) index and proximity index failed to correctly rank sites. The directional leakiness and lacunarity indices can be calculated for any remotely-sensed imagery that is of sufficient resolution to measure landscape patchiness at scales where processes of resource conservation are operating. For example, imagery of 0.2–1 m pixel sizes from arid and semi-arid rangelands can be classified into flow-obstructing patches and open non-obstructing interpatches. Such classified imagery and leakiness or lacunarity indicators can then be used to monitor changes in the resource retention potential of these landscapes. However, the applicability of these indicators for monitoring more humid vegetation types, and for assessing larger landscape areas (i.e. at coarser scales), needs to be evaluated.
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## 1. Introduction

Globally, there is concern for natural landscapes that are losing vegetation cover or suffering accelerated soil erosion, particularly if those landscapes, such as rangelands, are important for food and fiber (Williams

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et al., 1995; Fredrickson et al., 1998; Arnalds, 2000). Landscapes can be viewed as systems composed of two or more functionally linked land units (Risser, 1987), such as a hill-slope adjacent to a lower alluvial plain. These landscapes can also be viewed as systems that function to conserve resources by capturing run-off and retaining soils (Ludwig and Tongway, 2000). For example, a landscape is highly functional or non-leaky if it has structures or obstructions that prevent water, soil particles, and organic materials from running off or blowing out of the system (Tongway and Ludwig, 1997). At the opposite end of a continuum, a landscape is highly dysfunctional or leaky if it is bare and loses these resources. The size of the landscape system being viewed depends on one's research or management objectives (Risser, 1987). We are primarily interested in landscape systems of several hectares up to a few square kilometers (Ludwig et al., 2000).

The cover of vegetation patches has been shown to be a useful indicator of how well arid and semi-arid landscapes retain water and nutrients (Tongway and Ludwig, 1997). In Australia's mulga (*Acacia aneura*) woodlands, vegetation is often structurally organized into distinctive patches of trees separated by open interpatches, with these patch–interpatch units repeating down local topographic gradients (Ludwig and Tongway, 1995). These repeating landscape units of vegetation patches and interpatches function to capture and retain resources where, for example, water and nutrients lost from an up-slope interpatch are captured by the tree patch below it. At even finer scales of patchiness, clumps of grasses function to capture water and nutrients eroding from adjacent open interpatches (Tongway and Ludwig, 1994). Of course, resource retention will naturally be poor on erodable soil types, open vegetation types, on steep, exposed slopes, and at the extreme, in urban landscapes, which retain few resources and storm drains are required.

Directly measuring the capture of water and nutrients by landscape patches is very time-consuming and costly (Valentin et al., 1999); therefore, simple indicators of these landscape processes have been devised (Tongway and Ludwig, 1997). Four vegetation patch measures have been used as indicators of the potential of a landscape to retain resources: the cover and number of patches, the mean obstruction width of patches, and the mean fetch length or distance between patches (Ludwig and Tongway, 2000). In addition to these simple vegetation patch measures, the arrangement of patches within a landscape is also important for how well water and nutrients are retained and utilized for plant production (Ludwig et al., 1999a).

Measuring these vegetation patch attributes, as indicators of resource retention, has usually been done along field-based line-transects (Ludwig and Tongway, 1995). However, these measures only provide a linear sample of the landscape and remote-sensing methods, including near-ground digital photography, aerial videography and high-resolution satellite imagery, are now being used to provide a broader spatial sample (a belt) of vegetation patches for a local landscape (Northup et al., 1999; Kinloch et al., 2000; Pickup et al., 2000). Provided these images are of sufficient resolution to measure patch structures and patterns at a scale relevant to operating landscape processes, they have the advantage of providing a much broader view of landscape patchiness than measures derived from on-ground line-transect data.

In this paper, we use high-resolution aerial videography data to compare four landscape patch metrics in terms of their value for indicating the potential for a landscape to retain resources. These four indicators are the landscape metrics: leakiness, lacunarity, weighted mean patch size (WMPS), and proximity. The videography data were from two locations within Australia's arid and semi-arid rangelands. At each location we used two strongly contrasting sites: one, where ground inspection and descriptive vegetation information about the site indicated that the landscape was functioning well to retain resources; and the other, where similar information indicated that the landscape was highly dysfunctional (poorly conserving resources).

## 2. Study sites

The four study sites were located in two regions of the NT, Australia: Kidman Springs in the wet–dry tropical Victoria River District (median annual rainfall = 640 mm) and Mt. Riddock about 1000 km to the SSE, in the arid subtropical Alice Springs District (median annual rainfall = 240 mm) (Fig. 1a).

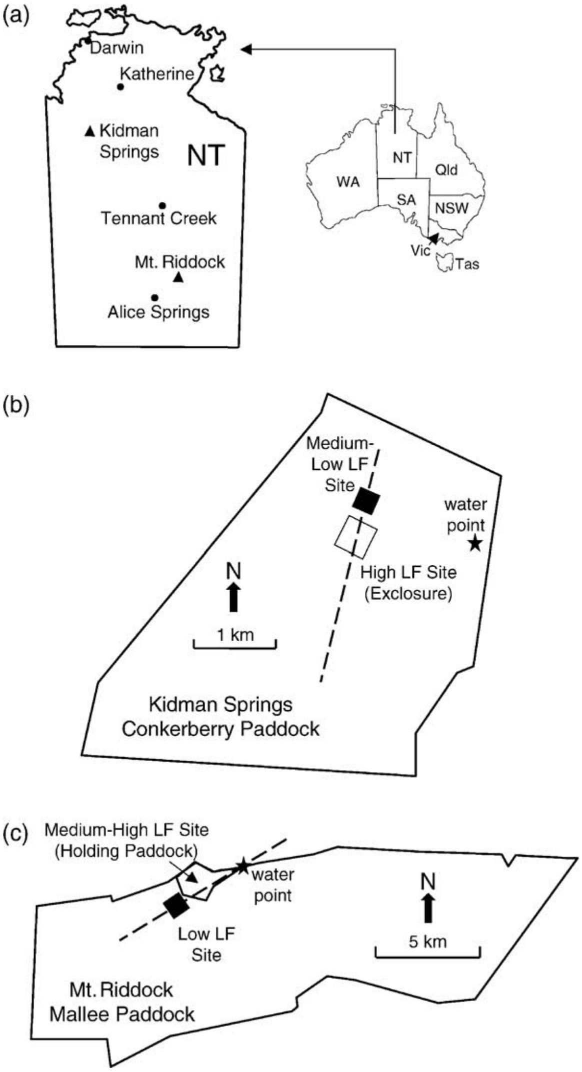


Fig. 1. The NT, Australia showing (a) the location of Kidman Springs and Mt. Riddock in relation to the main towns, and study sites with high to low landscape functionality (LF) at (b) Kidman Springs and (c) Mt. Riddock. Flight lines used for video imagery are shown by the dashed lines.

### 2.1. Kidman Springs

Two sites were positioned within Conkerberry Paddock about 1.5 km west of a water source for cattle grazing (Fig. 1b). The general vegetation is eucalypt savanna, and soils on both sites are calcareous red loams belonging to the calcareous red earth soil family (Gc1.22; Northcote et al., 1975). The first site is within an exclosure built in 1973 (Foran et al., 1985), and after 27 years of protection from livestock grazing has a high cover of large vegetation patches with a short mean distance between these patches, negligible bare soil exposed and no visible evidence of erosion (Table 1). In this exclosure, the vegetation is dominated by numerous, large clumps of perennial grasses (Fig. 2a), including curly bluegrass (*Dichanthium fecundum*), black speargrass (*Heteropogon contortus*) and limestone grass (*Enneapogon polyphyllus*). This site is rated as being the most highly functional (rank = 1; Table 1) in terms of its potential to retain resources (Ludwig et al., 1999b).

The other Kidman Springs site is located outside this exclosure and is subject to livestock grazing. This site is characterized by large areas of bare soil and evidence of past wind erosion and watersheeting. The vegetation comprises low annual grasses, mostly false couch (*Brachyachne convergens*) (Fig. 2b). In terms of its potential to conserve resources (Ludwig et al., 1999b), this site is rated as being moderately dysfunctional or of medium-low functionality (rank = 3; Table 1).

### 2.2. Mt. Riddock

The two Mt. Riddock sites are arid woodlands with gradational non-calcareous clay loam soils (Gn2.12/2.13; Northcote et al., 1975). The first site was located within an intermittently grazed holding paddock in Mallee Paddock 2 km south west of a cattle water point (Fig. 1c). This site had visually stable soil and a vegetation cover comprising scattered gidyea (*Acacia georginae*) and cottonbush shrubs (*Maireana aphylla*) interspersed amongst dense ungrazed patches of perennial grasses such as neverfail (*Eragrostis xerophila*) and introduced buffel grass (*Cenchrus ciliaris*) (Fig. 2c). These perennial grass clumps were relatively large (mean size = 1.7 $m^2$) and their cover was about 40%, and we rated this site as having a medium-high functionality or potential to retain resources (rank = 2; Table 1).

The other Mt. Riddock site has sparse acacia shrubs (mulga (*A. aneura*) and gidyea) with very scattered tussocks of grazed perennial neverfail and sparse annual grasses (mainly *Aristida contorta*) and forbs

Table 1
Ratings and rankings of landscape functionality or potential to retain resources for two sites at Kidman Springs and for two sites at Mt. Riddock in the NT, Australia

| Site | Landscape functionality | | Visual evidence of erosion | Mean interpatch spacing[a] (m) | Mean patch cover (%) | Mean patch size ($m^2$) | Bare soil cover (%) |
|---|---|---|---|---|---|---|---|
| | Rating | Rank | | | | | |
| Kidman Springs | High | 1 | Nil | 0.07 | 81.0 | 13.8 | 0.9 |
| Mt. Riddock | Medium-high | 2 | Nil | 0.62 | 37.6 | 1.7 | 45.6 |
| Kidman Springs | Medium-low | 3 | Past watersheeting | 1.53 | 11.0 | 0.7 | 28.7 |
| Mt. Riddock | Low | 4 | Active watersheeting | 2.78 | 6.0 | 0.8 | 89.4 |

Landscape attributes for these sites, as derived from aerial videography, include the spacing, cover, and mean size of perennial vegetation patches, and the extent of bare soil.
[a] Calculated as the mean Euclidean distance between adjacent patch edges.

(*Sclerolaena* spp.) (Fig. 2d). Perennial grass clumps were relatively small ($0.8\,m^2$), forming a low ground cover (6%). There was evidence of active watersheeting, and erosion control structures (ponding banks) had been built adjacent to our site to halt active gullying (Bastin, 1991). We rated this site as highly dysfunctional, i.e. with low potential to conserve resources (rank = 4; Table 1).

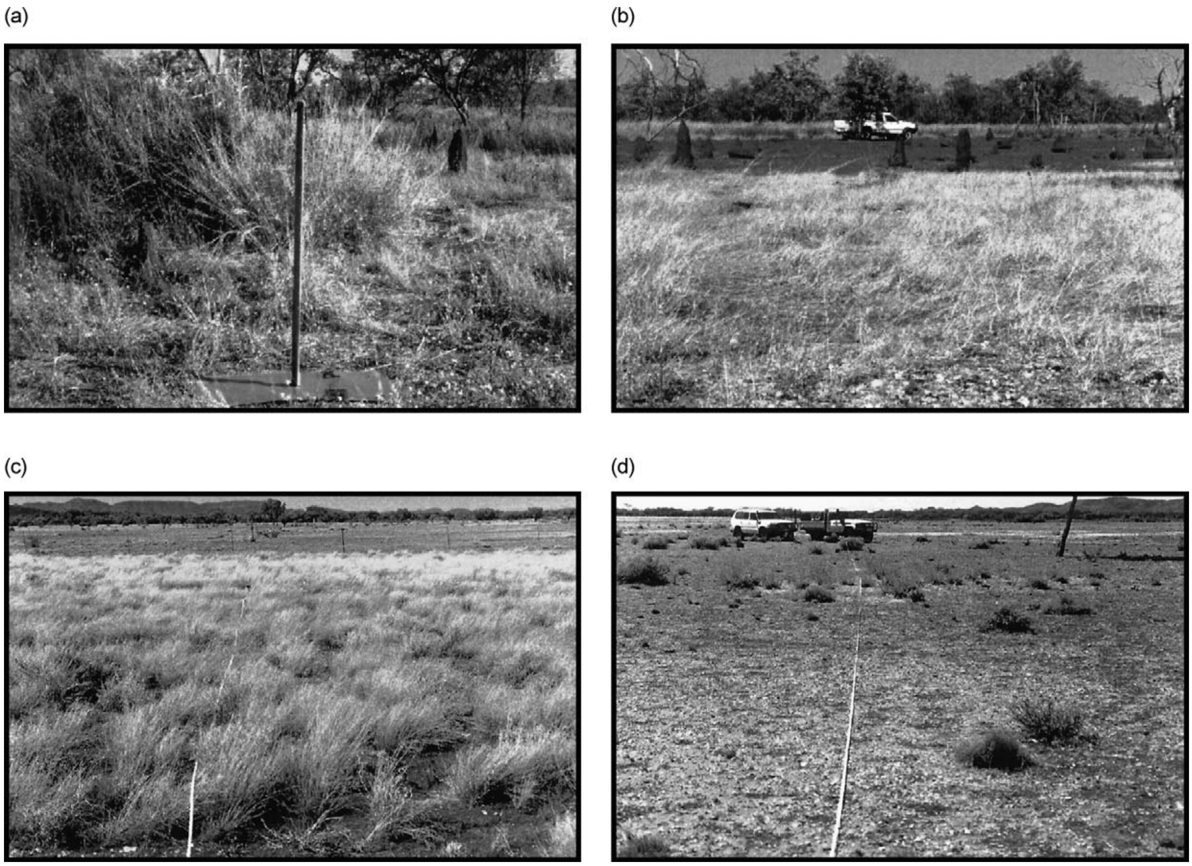

Fig. 2. Kidman Springs (KS) sites of (a) high and (b) medium-low landscape functionality (LF) or potential to retain resources, and Mt. Riddock (MR) sites of (c) medium-high and (d) low LF.

## 3. Aerial videography

The imaging equipment was a Specterra Systems digital multi-spectral video (DMSV) system consisting of four Cohu charge-coupled device cameras. Each camera was fitted with a 25 nm bandwidth interference filter centered on 450 nm (blue), 550 nm (green), 650 nm (red) and 770 nm (near infrared) producing multi-spectral images. The camera system was flown in a Cessna 206 and digital data were captured directly to an industrial-standard personal computer. Images were acquired at 280 m above the ground at Kidman Springs in September 1998 to produce a pixel size of 20 cm. Similar imagery, acquired at 470 m elevation and 33 cm pixel resolution, was flown at Mt. Riddock in June 1999. Image size at Kidman Springs was 150 m in the direction of flight and 115 m wide while at Mt. Riddock, images were 245 m by 190 m. Overlap between adjacent frames was approximately 20%.

Images were corrected with largely automated techniques to remove spatial distortion arising from camera operation (Pickup et al., 1995a) and spectral variation due to lens effects and viewing and illumination geometry (Pickup et al., 1995b). Adjoining images were mosaiced to provide continuous coverage of each site. The site imagery was then categorized into patches, corresponding with perennial vegetation and interpatches comprising bare soil, annuals and litter, using sequential classification techniques (Bastin et al., 1998; Pickup et al., 2000).

Spectrally distinct features such as shadow (low digital numbers (dn) in the visible bands) and bright bare soil (high dn) were first identified and masked from the mosaiced image. Simple ratios and transforms of the spectral data were then used to progressively map other features, e.g. trees with green canopies had high values of near infrared/red, blue-colored trees (*E. pruinosa*, *A. georginae*) had high blue/red values, and bare red soil had low PD54 values (Pickup et al., 1993). We concentrated throughout on accurately identifying trees, shrubs and perennial grasses in the mosaiced imagery because these constituted vegetation patches. The size of perennial grass tussocks generally created texture in the video images aiding their separation from annual herbage. This separation was also assisted when imagery was acquired at a time interval after rain where perennial grasses retained residual greenness and annuals had matured to a brighter straw color. Shadows cast by trees and shrubs were included as “patch” because it was likely that they concealed perennial grasses growing beneath them. The cover, size, and spacing of patches varied between sites (Table 1). Interpatch spacing was calculated as the mean distance between adjacent patch edges.

Ground-truthing confirmed a close agreement between the location of patches and interpatches observed on the ground and identified in the video imagery at the Kidman Springs and Mt. Riddock sites. This was done by relating mapped classes on imagery to measured aerial cover along ground-based transects of >100 m length. Testing of classified aerial videography elsewhere has also shown close agreement between ground-based measurement of vegetation cover and patches of perennial vegetation on imagery (Ludwig et al., 2000; Pickup et al., 2000). Hence, appropriately classified video images provide suitable vegetation patch data for computing indices of landscape function (Kinloch et al., 2000) and for comparing them. Following classification, the 20 cm Kidman Springs imagery was resampled to 33 cm pixel size to bring this imagery to the same resolution as the Mt. Riddock imagery before calculating the four landscape metrics as indicators of potential resource retention.

## 4. Indicators of landscape resource retention

Four landscape metrics were compared relative to our ranking of sites. We chose these metrics because their formulations appeared to encapsulate at least some of the attributes of landscape patchiness that we associate with how landscape systems function to retain resources such as litter and soil particles that are flowing in run-off or blowing in winds. Obviously the potential of a landscape to retain resources is high if the number and cover of surface obstructions (e.g. perennial vegetation patches) are large (Tongway and Ludwig, 1997), whereas a landscape with only a few small obstructions (i.e. leaving large open areas) will readily leak essential resources. Of course, other landscape attributes such as soil type and slope affect landscape leakiness. For example, a very flat landscape with stable soils will retain more resources than a steep landscape with erodable soils. However, given these other attributes are similar, the cover of perennial vegetation patches (viewed as surface obstructions) is of itself a useful indicator for comparing landscapes in terms of their potential to retain resources.

However, the percent ground cover of perennial vegetation patches or other surface obstructions (e.g. logs and rocks) is only part of the story because the size, shape, orientation, and dispersion of these patches is also very important for determining how well a landscape retains resources. For example, landscapes with bands of vegetation oriented along slope contours will capture more water and produce a greater plant biomass than landscapes with spotted patterns of vegetation patches (Ludwig et al., 1999a; Valentin et al., 1999).

### 4.1. Landscape leakiness index

Recently, an index for the potential of a landscape to leak (not retain) resources has been derived that is logically related to not just patch cover, but also to the number and size of patches and to the shape, orientation and dispersion of these patches across a landscape (Ludwig et al., 2002). This index, the directional leakiness index (DLI) assumes that the direction of resource flow is known; although if unknown, a variant of DLI, the multi-directional leakiness index (MDLI), can be computed. DLI also assumes that a remotely-sensed image can be rotated so that the direction of flow is down columns of the image. Each pixel in this image is classified as being patch or non-patch, with adjacent patch pixels forming patches and areas of non-patch pixels forming interpatches. Using these patch–interpatch data, DLI measures the relative leakiness of a landscape, i.e. how likely it is to lose (not retain) resources.

Briefly, resource leakiness as DLI is equal to one minus retention, where retention is computed as the sum of squares of the observed distances, $L_{\mathrm{obs}}$ (m), of all interpatch lengths in all columns of the classified image (Ludwig et al., 2002). This $L_{\mathrm{obs}}$ is scaled to a standard area (e.g. 1 ha for the coverage typically provided by high-resolution aerial videography) using proportional image dimensions. The scaled $L_{\mathrm{obs}}$ is expressed relative to a maximum leakiness for the image ($L_{\mathrm{max}}$), which assumes there are no obstructing patches in the landscape (for a standard 1 ha area, $L_{\mathrm{max}} = 1{,}000{,}000$). Finally, a minimum leakiness ($L_{\mathrm{min}}$) is computed assuming that the image is totally covered with obstructions that trap all resources, hence $L_{\mathrm{min}} = 0$.

Given these terms, the DLI is computed as

$$\mathrm{DLI} = 1 - \text{resource retention} = 1 - \left(\frac{L_{\mathrm{max}} - L_{\mathrm{obs}}}{L_{\mathrm{max}} - L_{\mathrm{min}}}\right)^{k}.$$

Resource retention ranges from 0 (no potential to retain resources) to 1 (full potential), hence, DLI ranges from 1 (totally leaky) to 0 (non-leaky). When plotted against percent patch cover, DLI takes the form of a decay curve with the parameter $k$ determining the steepness of the curve. We used $k = 5$ because this parameter value provides a good fit to data from field studies (Ludwig et al., 2002).

### 4.2. Weighted mean patch size

This index combines the number and size of patches and has been shown to provide a robust measure of how vegetation structure changes over time in response to disturbances (Li and Archer, 1997). As noted earlier, vegetation patch number and size have been used as simple indicators of the potential for landscapes to capture and retain water and nutrients (Tongway and Ludwig, 1997). Therefore, an index that combines these two patch attributes as mean patch size should also be a useful indicator of resource retention. For example, a landscape with many small patches will retain resources more efficiently than one with the same amount of patch cover arranged as a few large patches (Ludwig et al., 1999a).

The same mean patch size can be obtained with various combinations of patch size and number. To overcome this problem, Li and Archer (1997) derived a new index, WMPS. This index is based on percolation theory. Given that the number of patches $n$ of size $s$ is $n_s$, there is a probability, $n_s s$, that a cell (pixel) is occupied by this patch size class. There is also a probability, $\sum(n_s s)$, that a given patch size class occurs within the entire set of cells (pixels) in the image. For this, a weight for each patch size class $w_s$ is then computed as

$$w_s = \frac{n_s s}{\sum(n_s s)},$$

which is the probability that a given patch size class will occupy exactly $s$ cells. From these probabilities,

$$\mathrm{WMPS} = \sum (w_s s).$$

### 4.3. Lacunarity index

This index has been applied to landscape maps and remotely-sensed images to measure fragmentation (Plotnick et al., 1993; Peralta and Mather, 2000; Wu et al., 2000). Basically the lacunarity index is a measure of the distribution of 'holes' or 'gaps' in a spatial grid (pixel) map. Obviously a landscape with many large holes is likely to be much more 'leaky' in terms of its ability to retain resources than is a landscape with a few small holes. Because it measures these holes in a landscape, the lacunarity index is likely to be a good indicator of the potential of a landscape to capture and retain resources, i.e. to be non-leaky.

This index is based on lacunarity analysis, a method suggested by Mandelbrot (1983). Basically, a 'gliding box' or 'moving window' of a specified linear dimension $d$, (say $d = 2$) pixels, and square area ($d^2 = 4$) is used to exhaustively sample gridded data (e.g. a video image with each pixel classified into a patch type). The 'box' is initially positioned in one corner and the number of 'habitat pixels of interest' is counted within the box (Plotnick et al., 1993; McIntyre and Wiens, 2000). We counted the number of interpatch pixels in the box because our 'habitat pixels of interest' were the bare or open interpatch pixels. It is these openings that indicate the potential of a landscape to retain resources. A landscape that has large openings or 'gaps' is unlikely to retain resources (i.e. will be more leaky) and will have a low lacunarity value (low resource retention). A landscape covered with fewer open pixels and more vegetation patch pixels will have a higher lacunarity value (higher resource retention).

The box is moved one pixel to the right and the pixel count repeated. This moving and counting is done for each possible row and column for the image map. These counts are summarized as a frequency distribution, which is then expressed as a probability distribution by dividing each frequency value by the total number of gliding boxes for a given size. Lacunarity was then computed from this probability distribution as the variance divided by the square of the mean count per gliding box for its size:

$$\Lambda = \left(\frac{\text{variance}}{\text{mean}^2}\right) + 1.$$

This lacunarity index was determined for selected box sizes with linear dimensions varying from 1 to 50 m.

### 4.4. Proximity index

This index defines the spatial context of landscape patches in relation to their neighbors (Gustafson and Parker, 1994). The proximity index combines spatial information on patch size and spacing, and will clearly distinguish a site with small patches distantly spaced from a site with large patches closely spaced. If these are perennial vegetation patches, intuitively, the latter site will more efficiently retain resources flowing or blowing about the landscape than the former. A site with larger and more closely packed vegetation patches will provide more obstructions to trap wind-blown litter and soil particles, and any such particles flowing in run-off (Tongway and Ludwig, 1997). Thus, the proximity index may provide a useful indicator for the potential of a landscape to capture resources.

The proximity index (PX) can be applied to a map with each patch of interest spatially located (e.g. a classified aerial video image). The index is calculated by first identifying each patch which lies within a specified distance (i.e. number of pixels) from a specified patch, $i$, with each patch within the map taken in turn (Gustafson and Parker, 1994). This distance is called the proximity buffer. Then the edge-to-edge distance, $x_i$, from patch $i$ to its nearest-neighbor patch is determined for each of $n$ patches within the proximity buffer. Given the size of each patch $s_i$, PX is computed as the summation over $n$ patches of $s_i$ divided by $x_i$; that is

$$\mathrm{PX} = \sum \frac{s_i}{x_i}, \quad \text{for } i = 1\text{–}n;$$

see Gustafson and Parker, 1994.

## 5. Results

Landscape leakiness showed a marked separation between the site that retained resources well (Kidman Springs high LF) and a site which did not (Mt. Riddock

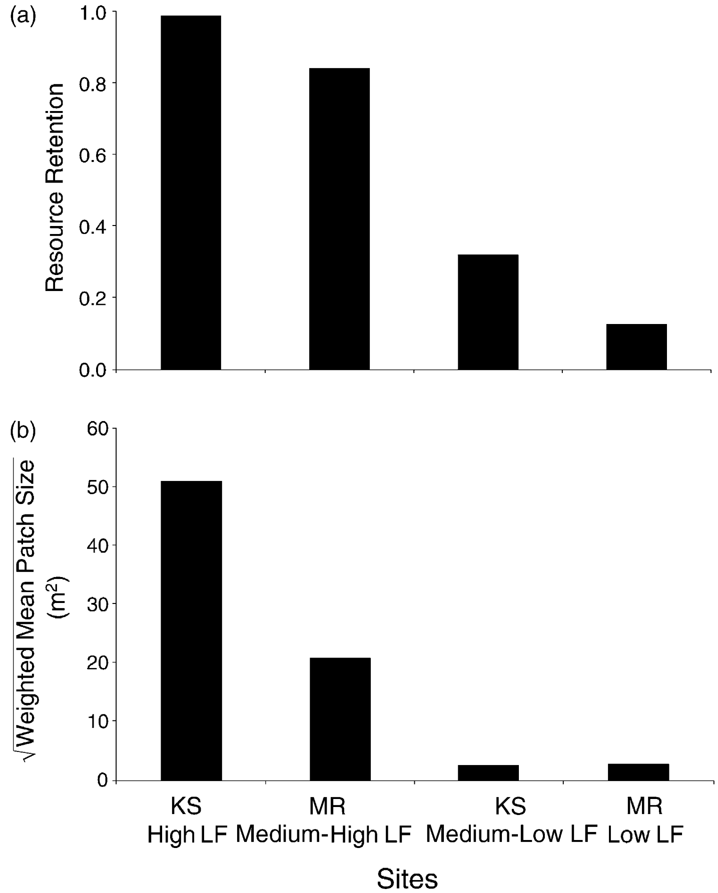


Fig. 3. For sites of high to low landscape functionality (LF) at Kidman Springs (KS) and Mt. Riddock (MR): (a) resource retention, as converse of the directional leakiness index, and (b) square root of weighted mean patch size.

low LF) (Fig. 3a) (note, that to visually keep Fig. 3a in the same form as Fig. 3b, and as Figs. 4b and 5b where high values represent high landscape functionality, we plotted the retention component of the DLI, where leakiness $= 1 -$ retention). This difference in resource retention between these two sites is visually evident by comparing Fig. 2a with Fig. 2d. The other two sites were intermediate between these two extremes, with the Mt. Riddock medium-high LF site having a higher potential for resource retention, hence a lower leakiness, than the Kidman Springs medium-low LF site.

The Kidman Springs high LF site had the highest mean patch size ($13.8\,m^2$; Table 1). Because WMPS uses the square of patch size class in its calculation, this site had a very large WMPS (WMPS $= 2584\,m^2$), making it necessary to use a square root transform ($\sqrt{\text{WMPS}} = 51$) to display it against sites of lower potential to retain resources, whose values were very much smaller ($\sqrt{\text{WMPS}} < 3$, Fig. 3b). All sites had a skewed distribution of patch size classes with many small patches and few large patches, but this was particularly the case at the Kidman Springs high LF site where patches had coalesced to form a nearly continuous perennial vegetation cover, hence, some very large patches.

Lacunarity values are affected by the size of the gliding box used to exhaustively sample an image classified into patch and interpatch pixels (Plotnick et al., 1993; Wu et al., 2000). As box sizes increase,

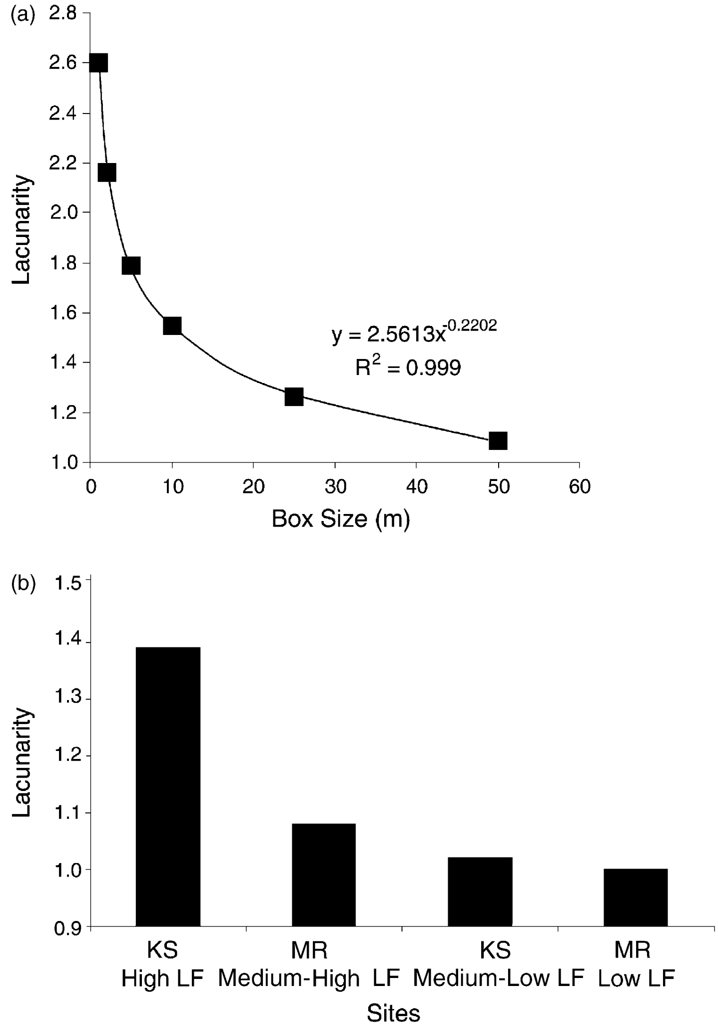


Fig. 4. Lacunarity index values: (a) at different sizes of a gliding box as calculated for the Kidman Springs high LF site, and (b) at the 10 m box size for sites of high to low landscape functionality (LF) at Kidman Springs (KS) and Mt. Riddock (MR).

lacunarity scores decrease, as illustrated for the Kidman Springs high LF site (Fig. 4a). Although such curves could be determined for each site and compared, which can yield useful information (Plotnick et al., 1993), we chose to compare sites using a bar chart for a fixed box size. We selected a 10 m box to compare sites because this size is at an intermediate point along the lacunarity versus box size curves (Fig. 4a).

The Kidman Springs high LF site had the highest lacunarity value (Fig. 4b) indicating a landscape with few small ‘holes’ or openings, hence high resource retention potential or low leakiness. The Mt. Riddock low LF site had the lowest lacunarity index, but there was little separation between this site and the Kidman Springs medium-low LF site, both with lacunarity values near 1.0.

Mean proximity (PX) values increased at all sites as buffer size increased (Fig. 5a), with the separation between sites also increasing with buffer size. The site rated as most conserving (Kidman Springs high LF) had the lowest mean PX values over all buffer sizes and

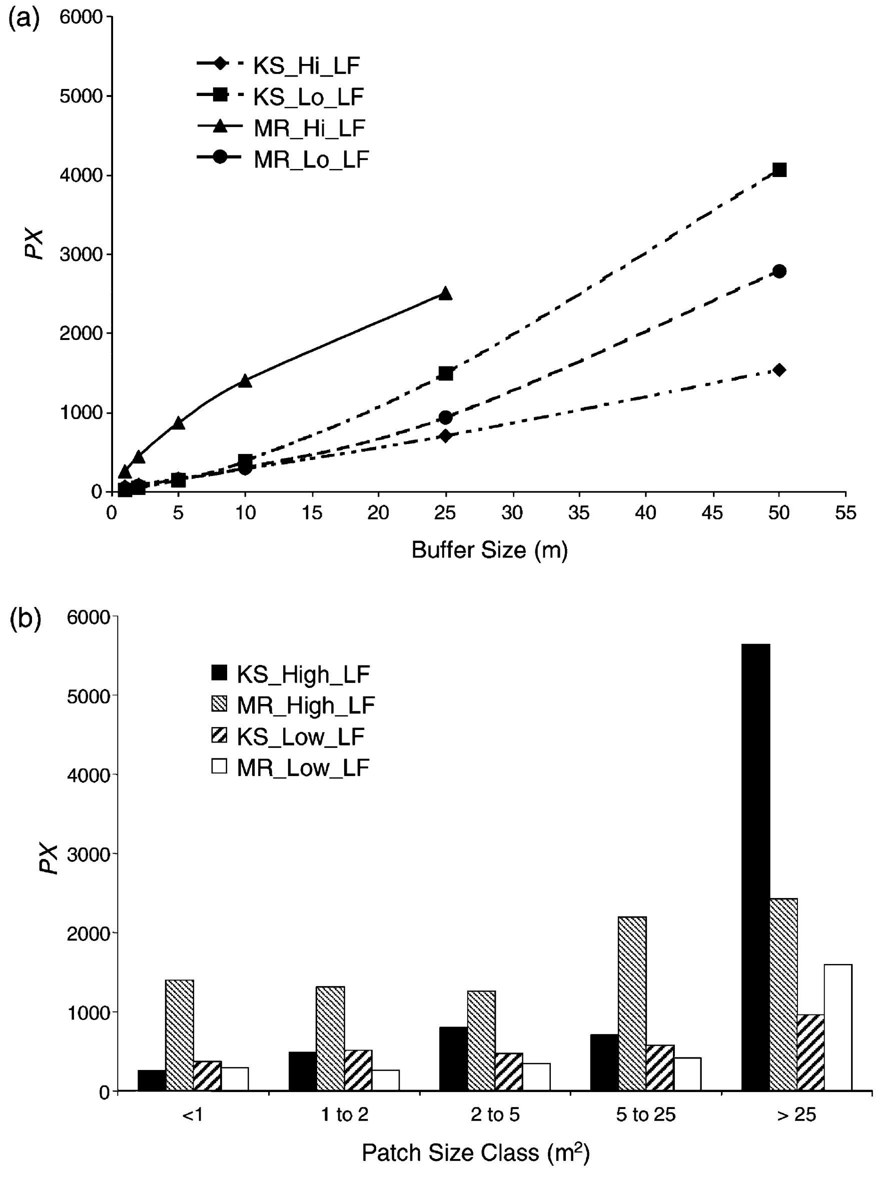


Fig. 5. Mean proximity index (PX) values for sites of high to low landscape functionality (LF) at Kidman Springs (KS) and Mt. Riddock (MR): (a) at different buffer sizes (m), and (b) across patch size classes ($m^2$). Note, there is no PX value for the 50 m buffer size at the MR medium-high LF site because the landscape area available for analysis was too small.

the Mt. Riddock medium-high LF site had the highest values (small site area precluded a PX for the 50 m buffer size). The site rated as least conserving (Mt. Riddock low LF) had slightly higher PX values than the most conserving site (Kidman Springs high LF).

Although, mean PX values generally increased with increasing patch size class at all sites, there were deviations from this pattern amongst sites at the different patch size classes (Fig. 5b). For example, the Kidman Springs high LF site had a lower PX value than the

Table 2
Rankings for landscape patchiness metrics relative to the ratings and rankings of landscape functionality or potential to retain resources on four sites where 1 = highest and 4 = lowest

| Site | Landscape functionality | | Landscape patchiness metrics | | | |
|---|---|---|---|---|---|---|
| | Rating | Rank | Landscape leakiness index | Weighted mean patch size | Lacunarity index | Proximity index |
| Kidman Springs | High | 1 | 1 | 1 | 1 | 4 |
| Mt. Riddock | Medium-high | 2 | 2 | 2 | 2 | 1 |
| Kidman Springs | Medium-low | 3 | 3 | 3.5[a] | 3 | 2 |
| Mt. Riddock | Low | 4 | 4 | 3.5[a] | 4 | 3 |

See Table 1 and Fig. 2.
[a] Values, hence ranks, approximately equal.

Kidman Springs medium-low LF site for the smallest patch size class, but this pattern was reversed at patch size classes greater than $5\,m^2$. The most leaky site (Mt. Riddock low LF) had the lowest mean PX values for most size classes, and unexpectedly, the Mt. Riddock medium-high LF site had higher mean PX than the Kidman Springs high LF site, except at the largest patch size class (>$25\,m^2$).

Of the four landscape metrics examined, only the leakiness index, or its converse, resource retention, and the lacunarity index ranked sites in the expected order of rated landscape functionality or their potential to conserve resources (Table 2). WMPS failed to distinguish the two low-functionality sites, one at Kidman Springs and the other at Mt. Riddock. The proximity index failed to rank sites according to their rated functionality.

## 6. Discussion

In this study, we included the landscape DLI because it has been shown to be logically related to those landscape attributes such as vegetation patch cover that indicate the potential of arid and semi-arid landscapes to retain resources (Ludwig et al., 2002). Many studies have shown the importance of vegetation cover in increasing infiltration and reducing soil loss through increased run-off and wind erosion (Johns, 1983; Lang and McCaffrey, 1984; Leys, 1991; McIvor et al., 1995; Galle et al., 1999; Carroll and Tucker, 2000). In arid and semi-arid rangelands, where vegetation amount can vary considerably with erratic rainfall (Foran, 1987), persistent cover provided by perennials is important in minimizing loss of soil and water.

The DLI relates the cover, number and size of patches, and their arrangement (i.e. shape, orientation and dispersion) to resource (soil) losses from a landscape, where the curve parameter $k$ defines this relationship (Ludwig et al., 2002). This parameter can be varied from the value of 5 used here to fit DLI to soil loss versus patch cover data, if such data are available for a specific landscape. As a leakiness or resource retention index, DLI is particularly appealing because it can be rapidly and easily calculated for imagery of any size, pixel resolution or shape that can be classified into flow-obstructing patches and open interpatches (Ludwig et al., 2002). Such patchiness is distinctive for many arid and semi-arid deserts, grasslands, shrublands, woodlands and savannas (Fredrickson et al., 1998; Ludwig et al., 1999c; Valentin et al., 1999; Kinloch et al., 2000). How well DLI applies to wetter landscapes with less distinctive patches and interpatches, remains to be tested.

We used the lacunarity index, which measures the spatial pattern of gaps between patches, because this landscape metric has been applied to the analysis of satellite imagery of forest patches to detect changes in these landscapes (Peralta and Mather, 2000). It has also been applied to habitat fragmentation (Plotnick et al., 1993; Wu et al., 2000) and to quantify patterns of habitat and non-habitat use by animals (McIntyre and Wiens, 2000). It has also been used to measure the intensity of spatial pattern in maps of patches and gaps or interpatches (Dale, 2000). We found lacunarity values accurately indicated the relative functionality of landscapes to retain resources, although these values did not separate the two low-functionality sites as effectively as did the leakiness index. Wu et al. (2000) similarly reported success in using lacunarity to characterize fragmentation of woody cover and associated retention of rainfall on sites in tiger bush landscapes in Niger.

Applying lacunarity as an indicator of the potential for landscapes to retain resources does require that an appropriate box size be selected for the patches and gaps on the sites being investigated. A 10 m box size was sensible for our test sites because it fitted within the vegetation patches of high-functionality sites and within the interpatch gaps of the low-functionality sites. A much larger box size (perhaps >50 m) may be necessary for coarser resolution imagery and/or larger vegetation structures, such as banded *Acacia* shrublands (Ludwig and Tongway, 1995) or tiger bush landscapes (Wu et al., 2000).

We examined WMPS because it combines the number and size of patches (Li and Archer, 1997), attributes related to the potential for a landscape to retain resources. WMPS produced a greatly exaggerated separation between the most conserving site and the other three sites because of the weighting (squaring of patch sizes) imposed by this index. On landscapes with high functionality or potential to retain resources, such as that within the exclosure at Kidman Springs, vegetation patches tend to coalesce and form a few large patches. Squaring the size of these large patches greatly inflates WMPS values. Transforming these WMPS values will reduce the separation caused by extreme values (e.g. square root of WMPS; Fig. 3b). Such transforms may not be needed when comparing landscapes where all the vegetation patches are smaller and more discrete. For example, Kinloch et al. (2000) found that WMPS did usefully differentiate sites located at increasing distances from a sheep watering point in an arid chenopod shrubland in southern Australia.

The proximity index was evaluated because it incorporates information about patch size, spacing, and arrangement (Gustafson and Parker, 1994), and would intuitively seem useful for indicating the potential for a landscape to retain resources. However, this index did not consistently rank sites in relation to their rated landscape functionality. This failure may be due to the fact that PX values are strongly dependent on how landscape attributes, such as patch size, the spacing between patches, the size of neighbor patches within a buffer region, and the size of this buffer region interact. For example, pixels must first be grouped into larger patches and these patches do not have to be entirely contained within a buffer region to contribute to a PX value (Gustafson and Parker, 1994). Perhaps, these interactions and dependencies in PX do not reflect landscape functionality very well.

The leakiness index and the lacunarity index perfectly ranked four rangeland sites according to their ratings of landscape functionality or potential to retain resources. Two of these sites were located in an area with a median annual rainfall of 640 mm and the other two sites were located in a more arid area with a median annual rainfall of 240 mm. Subsequent testing of a more extensive remotely-sensed dataset has shown that the leakiness index is robust across a broader rainfall gradient (Bastin et al., 2002). Index values were derived from aerial videography of clay, sand and loam sites at different latitudes from the monsoonal climate of northern Australia (where rainfall is higher, >640 mm, and reliable) to the very arid interior of Australia (where rainfall is <200 mm and highly variable). Potential to retain resources decreased as median annual rainfall decreased, and rainfall variability increased. This result emphasizes that rainfall redistribution through run-off and run-on is increasingly important for patch persistence as aridity increases. At each latitudinal setting, clay and sand sites generally had greater potential to retain resources than loam sites.

Our findings reported here have some potentially valuable applications. The first is for determining the health or condition of arid and semi-arid landscapes where remotely-sensed landscape features (patches and interpatches) can indicate the potential for the landscape to retain vital natural resources. The second is to assess whether the potential for a landscape to retain resources is improving or declining by analyzing multi-temporal imagery. Monitoring using other indices based on remotely-sensed data has proven valuable for establishing trends in land condition for grazing lands and other lands that are prone to desertification (Fredrickson et al., 1998; Pickup et al., 1998). To date, remotely-sensed satellite imagery has been used to detect changes in vegetation cover or 'greenness' (Pickup et al., 1994; Roderick et al., 1999). Although this provides valuable information, our findings demonstrate that one can also monitor change in terms of the potential of landscapes to capture and retain resources. Monitoring this landscape potential is now being recommended as an essential part of rangeland monitoring (Friedel et al., 2000; Tongway and Hindley, 2000).

In this study, we calculated metrics from classified images based on aerial videography data from arid and semi-arid landscapes at a local scale (ha scales). For monitoring the resource retention potential of other landscape types (e.g. sub-humid woodlands) at larger scales (e.g. $km^2$ scales), high-resolution, multi-spectral satellite imagery could be used, such as 4 m pixel multi-spectral imagery from IKONOS (Tanaka and Sugimura, 2001). However, in this case, it would be necessary to test that enlarged pixels are small enough to distinguish any flow-obstructing patches from non-obstructing interpatch openings in the landscape (Ludwig et al., 2002). In fine-grained landscapes, such as tussock grasslands, high-resolution satellite data may be inadequate to distinguish interpatch openings, and in temperate and humid woodland and landscapes, forest openings may not exist except with severe disturbance (e.g. cleared farmland). Where vegetation is more open (e.g. semi-arid woodland with banded vegetation, Ludwig and Tongway, 1995), the 4 m pixel size of IKONOS would be adequate.

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## References

Arnalds, O., 2000. Desertification: an appeal for a broader perspective. In: Arnalds, O., Archer, S. (Eds.), Rangeland Desertification. Advances in Vegetation Sciences, Vol. 19. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 5–15.

Bastin, G.N., 1991. Rangeland reclamation on Atartinga Station, central Australia. Aust. J. Soil Water Conserv. 4, 18–25.

Bastin, G.N., Chewings, V.H., Pearce, G., 1998. Verifying high-resolution satellite data using aerial videography. In: Proceedings of the Ninth Australian Remote Sensing Conference on CD-ROM, Sydney, Australia. Causal Productions, Adelaide, p. 10.

Bastin, G.N., Kinloch, J.E., Chewings, V.H., Pearce, G., Ludwig, J.A., Eager, R.W., Liedloff, A.C., 2002. In: Vegetation Patches: How Do They Change Along an Environmental Gradient? Range Management Newsletter, no. 02/1, in press.

Carroll, C., Tucker, A., 2000. Effects of pasture cover on soil erosion and water quality on central Queensland coal mine rehabilitation. Trop. Grasslands 34, 254–262.

Dale, M.R.T., 2000. Lacunarity analysis of spatial pattern: a comparison. Landsc. Ecol. 15, 467–478.

Foran, B.D., 1987. Detection of yearly cover change with Landsat MSS on pastoral landscapes in Central Australia. Remote Sens. Environ. 23, 333–350.

Foran, B.D., Bastin, G.N., Hill, B., 1985. The pasture dynamics and management of two rangeland communities in the Victoria River District of the Northern Territory. Aust. Rangeland J. 7, 107–113.

Fredrickson, E., Havstad, K.M., Estell, R., Hyder, P., 1998. Perspectives on desertification: south-western United States. J. Arid Environ. 39, 191–208.

Friedel, M.H., Laycock, W.A., Bastin, G.N., 2000. Assessing rangeland condition and trend. In: Mannetje, L., Jones, R.M. (Eds.), Field and Laboratory Methods for Grassland and Animal Production Research. CAB International, Wallingford, pp. 227–262.

Galle, S., Ehrmann, M., Peugeot, C., 1999. Water balance in a banded vegetation pattern: a case study of tiger bush in western Niger. Catena 37, 197–216.

Gustafson, E.J., Parker, G.R., 1994. Using an index of habitat patch proximity for landscape design. Landsc. Urban Plan. 29, 117–130.

Johns, G.G., 1983. Run-off and soil loss in a semi-arid shrub invaded poplar box (*Eucalyptus populnea*) woodland. Aust. Rangeland J. 5, 3–12.

Kinloch, J.E., Bastin, G.N., Tongway, D.J., 2000. Measuring landscape function in chenopod shrublands using aerial videography. In: Proceedings of the 10th Australian Remote Sensing Conference on CD-ROM, Adelaide, Australia. Causal Productions, Adelaide, pp. 480–491.

Lang, R.D., McCaffrey, L.A.H., 1984. Ground cover—its effects on soil loss from grazed run-off plots, Gunnedah. J. Soil Conserv., New South Wales 40, 56–61.

Leys, J.F., 1991. Towards a better model of the effect of prostrate vegetation cover on wind erosion. Vegetatio 91, 49–58.

Li, B., Archer, S., 1997. Weighted mean patch size: a robust index for quantifying landscape structure. Ecol. Model. 102, 353–361.

Ludwig, J.A., Bastin, G.N., Eager, R.W., Karfs, R., Ketner, P., Pearce, G., 2000. Monitoring Australian rangeland sites using landscape function indicators and robust ground and remote techniques. Environ. Monitor. Assess. 64, 167–178.

Ludwig, J.A., Eager, R.W., Bastin, G.N., Chewings, V.H., Liedloff, A.C., 2002. A leakiness index for assessing landscape function using remote-sensing. Landsc. Ecol., in press.

Ludwig, J.A., Eager, R.W., Williams, R.J., Lowe, L.M., 1999b. Declines in vegetation patches, plant diversity, and grasshopper diversity near cattle watering-points in the Victoria River District, northern Australia. Rangeland J. 21, 135–149.

Ludwig, J.A., Tongway, D.J., 1995. Spatial organization of landscapes and its function in semi-arid woodlands Australia. Landsc. Ecol. 10, 51–63.

Ludwig, J.A., Tongway, D.J., 2000. Viewing rangelands as landscape systems. In: Arnalds, O., Archer, S. (Eds.), Rangeland Desertification: Advances in Vegetation Sciences, Vol. 19. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 39–52.

Ludwig, J.A., Tongway, D.J., Eager, R.W., Williams, R.J., Cook, G.D., 1999c. Fine-scale vegetation patches decline in size and cover with increasing rainfall in Australian savannas. Landsc. Ecol. 14, 557–566.

Ludwig, J.A., Tongway, D.J., Marsden, S.G., 1999a. Stripes, strands or stipples: modeling the influence of three landscape banding patterns on resource capture and productivity in semi-arid woodlands. Aust. Catena 37, 257–273.

Mandelbrot, B.B., 1983. The Fractal Geometry of Nature. Freeman Publishing, New York.

McIntyre, N.E., Wiens, J.A., 2000. A novel use of the lacunarity index to discern landscape function. Landsc. Ecol. 15, 313–321.

McIvor, J.G., Williams, J., Gardener, C.J., 1995. Pasture management influences run-off and soil movement in the semi-arid tropics. Aust. J. Exp. Agric. 35, 55–65.

Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, C.H., Bettanay, E., 1975. A Description of Australian Soils. CSIRO, Melbourne, Australia.

Northup, B.K., Brown, J.R., Dias, C.D., Skelly, W.C., Radford, B., 1999. A technique for near-ground remote sensing of herbaceous vegetation in tropical woodlands. Rangeland J. 21, 229–243.

Peralta, P., Mather, P., 2000. An analysis of deforestation patterns in the extractive reserves of Acre, Amazonia from satellite imagery: a landscape ecological approach. Int. J. Remote Sens. 21, 2555–2570.

Pickup, G., Bastin, G.N., Chewings, V.H., 1994. Remote sensing-based condition assessment for non-equilibrium rangelands under large-scale commercial grazing. Ecol. Appl. 4, 497–517.

Pickup, G., Bastin, G.N., Chewings, V.H., 1998. Identifying trends in land degradation in non-equilibrium rangelands. J. Appl. Ecol. 35, 365–377.

Pickup, G., Bastin, G.N., Chewings, V.H., 2000. Measuring rangeland vegetation with high-resolution airborne videography in the blue-near infrared spectral region. Int. J. Remote Sens. 21, 339–351.

Pickup, G., Bastin, G.N., Chewings, V.H., Pearce, G., 1995b. Correction and classification procedures for assessing rangeland vegetation cover with airborne video data. In: Proceedings of the 15th Biennial Workshop on Videography and Color Photography in Resource Assessment. American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 305–314.

Pickup, G., Chewings, V.H., Nelson, D.J., 1993. Estimating changes in vegetation cover over time in arid areas from remotely-sensed data. Remote Sens. Environ. 43, 243–263.

Pickup, G., Chewings, V.H., Pearce, G., 1995a. Procedures for correcting high-resolution airborne video imagery. Int. J. Remote Sens. 16, 1647–1662.

Plotnick, R.E., Gardner, R.H., O'Neill, R.V., 1993. Lacunarity indices as measures of landscape texture. Landsc. Ecol. 8, 201–211.

Risser, P.G., 1987. Landscape ecology: state of the art. In: Turner, M.G. (Ed.), Landscape Heterogeneity and Disturbance. Springer, New York, pp. 3–14.

Roderick, M.L., Noble, I.R., Cridland, S.W., 1999. Estimating woody and herbaceous vegetation cover from time series satellite observations. Global Ecol. Biogeogr. 8, 501–508.

Tanaka, S., Sugimura, T., 2001. A new frontier of remote sensing from IKONOS images. Int. J. Remote Sens. 22, 1–5.

Tongway, D.J., Hindley, N., 2000. Ecosystem function analysis of rangeland monitoring data. Rangeland Audit Project 1.1 Report. National Land and Water Resources Audit, Canberra.

Tongway, D.J., Ludwig, J.A., 1994. Small-scale resource heterogeneity in semi-arid landscapes. Pacific Conserv. Biol. 1, 201–208.

Tongway, D.J., Ludwig, J.A., 1997. The conservation of water and nutrients within landscapes. In: Ludwig, J.A., Tongway, D.T., Freudenberger, D., Noble, J., Hodgkinson, K. (Eds.), Landscape Ecology, Function and Management: Principles from Australia's Rangelands. CSIRO, Melbourne, Australia, pp. 13–22.

Valentin, C., d'Herbes, J.M., Poesen, J., 1999. Soil and water components of banded vegetation patterns. Catena 37, 1–24.

Williams, M., McCarthy, M., Pickup, G., 1995. Desertification, drought and landcare: Australia's role in the international convention to combat desertification. Aust. Geogr. 26, 23–33.

Wu, X.B., Thurow, T.L., Whisenant, S.G., 2000. Fragmentation and changes in hydrologic function of tiger bush landscapes, south-west Niger. J. Ecol. 88, 790–800.