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# PROGRESSING THE CONCEPT OF LANDSCAPE FUNCTION FOR ASSESSING RANGELAND HEALTH

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## ABSTRACT

Assessing landscape function is now an established component of rangeland monitoring programs. In this paper, we focus on the spatial arrangement of perennial vegetation patches as a readily measured and useful indicator of landscape function. We demonstrate work in progress to verify indicators of landscape function. We then show how a recently developed directional leakiness index based on high resolution remotely-sensed imagery may allow up-scaling from ground-based assessment. Concurrent work involving simulation modelling of landscape processes is also contributing to this up-scaling. We explore the potential of satellite imagery, including recently available "hyper-spatial" and hyperspectral data, to continue this up-scaling to paddock-scale where the real decisions about land management are made. Where vegetation patches are predominantly comprised of palatable forage, there should be a direct link between index values of landscape function and stability of livestock production. But what is the corresponding relationship between landscape function and biodiversity? We discuss possible functional relationships and support these with examples where data are available. Finally we comment on potential developments that may improve the versatility of landscape functional analysis for monitoring rangelands for production and conservation outcomes.

## INTRODUCTION

Healthy grazing lands (rangelands) have been broadly defined as those landscapes "that function to (1) conserve resources by retaining water, soil and nutrients, (2) provide habitat for maintaining native plant and animal populations, and (3) meet the material, aesthetic and cultural needs of people living in these rangelands (Whitehead *et al.*, 2000). Although this working definition of landscape health was developed for the savannas of northern Australia, we view it as generally applicable to most landscapes.

In this paper, the first component of rangeland health, retention of resources, is examined by reviewing the concept of landscape function, which underpins rangeland monitoring and minesite rehabilitation at local scales. We discuss progress in verifying indicators of landscape function. We then demonstrate how the spatial arrangement of vegetation patches, which acts as a powerful indicator of landscape function, can be scaled up to larger areas using remote sensing and simulation modelling approaches. Finally, we explore ecological links between resource conservation and habitat quality and from that, the potential of patch arrangement to act as a surrogate for monitoring aspects of biodiversity status. We do not discuss the third component of rangeland health, that is, social and cultural aspects, apart from acknowledging their importance and emphasising that knowledge generated here needs to be integrated with resource retention and habitat-diversity information.

## A CONCEPT OF LANDSCAPE FUNCTION

Landscape function refers to the effectiveness of a landscape as a biophysical system and this reveals that the conservation of resources within landscapes is an important unifying concept (Ludwig *et al.*, 1997). This is similar to the principles articulated by Odum (1983) who used energy as his unifying principle. Landscapes styled as "functional" regulate the flux of vital resources so that their progress down slope is

slow and opportunities for absorption and cycling are high. Conversely, dysfunctional landscapes tend to lose or leak vital resources out of the system. There is a continuum between highly functional and dysfunctional landscapes.

Basically, semi-arid and arid rangelands are landscapes that are spatially organised as patchy systems comprised of a network of runoff and runon zones, where this structure functions to conserve scarce water and nutrient resources (Ludwig and Tongway, 2000). As soil and litter, and their nutrients, are redistributed by wind and water processes, some areas within the landscape are enriched through the accumulation of water and nutrients (i.e., form 'fertile islands'). These areas typically support a higher biomass of more persistent (perennial) vegetation. Correspondingly, adjacent areas that shed water and soil become more depauperate and are either bare or grow sparse ephemeral vegetation. This produces vegetation patterns critical for surface hydrological processes that conserve resources within the landscape. If these vegetation patterns are disrupted, the capacity for resource retention and the potential productivity of the landscape is reduced. Intact landscapes have patch arrangements that efficiently retain soil and litter carried by wind and water. As patch structures break down through disturbance, pathways for surface flow become more direct and nutrients and water progressively leak from the system.

We recognise that resource conservation may seem not to hold in some rangeland environments, or its relevance may appear disguised. Examples include tussock grasslands on flat cracking-clay soils, and temperate and sub-tropical grassy woodlands with annual rainfall in excess of about 600 mm. These areas may have grassy-sward ground layers not characterised by patchiness where resource regulation is effected by grass butt size and crown separation factors. Nevertheless, the principle of resource regulation holds at these and much higher rainfall regimes. We also recognise the importance of nutrient cycling in maintaining plant productivity often evident at the within-patch scale (see paper by Adams, this session) but argue that in many rangeland environments, resource redistribution through runoff and runon is a reality and that resource conservation is vital to maintaining biophysically functional landscapes.

## INDICATORS RATHER THAN DIRECT MEASUREMENT

Directly measuring the capture of water and nutrients by landscape patches is very time-consuming and costly (e.g., Valentin et al., 1999); therefore, simple indicators of these landscape processes are required for monitoring purposes (Ludwig and Tongway, 1995; Tongway and Ludwig, 1997; Ludwig and Tongway, 2000). We believe that an indicator in this context is a piece of information, easily acquired, that links scientific measurements to practical interpretations of landscape function. Sensible and useful indicators inform, are robust yet sufficiently sensitive to detect change, convenient and inexpensive to apply, capable of providing a predictive understanding of ecosystems when used with an appropriate conceptual framework and amenable to use by a range of operators after appropriate training. Where indicators are devised for directly informing land managers, as distinct from making data collection easier or more cost-effective for scientists, then joint ownership is essential. That is, users should relate to what the surrogate is indicating and have confidence in the information provided.

So what are simple and useful indicators of resource conservation? At the broader level of landscape organisation, they relate to the spatial arrangement of permanent vegetation patches. At a finer scale, patches (and associated interpatch spaces) may differ in their functional performance according to their differential responses to stresses and disturbances in the landscape. These fine-scaled changes can be assessed by soil surface indicators used at the within-patch and within-interpatch scale. It is at this finer scale that processes such as infiltration, runoff, deposition of sediment, litter decomposition and aggregate stability can be assessed. This is the basis for a monitoring procedure called "landscape function analysis", though it is fair to say that below-ground processes are explicitly not addressed. Indices reflecting soil stability, infiltration rate and nutrient cycling are derived from eleven simple indicators assessed by careful observation (Tongway and Hindley, 2000).

Progress is being made on verifying that these simple indicators are related to the measured variables that they purport to represent (Fig. 1). Good relationships have been found in rainfall regimes from 200 mm to 4000 mm annual rainfall for the infiltration and nutrient cycling indices (Tongway, unpublished data).
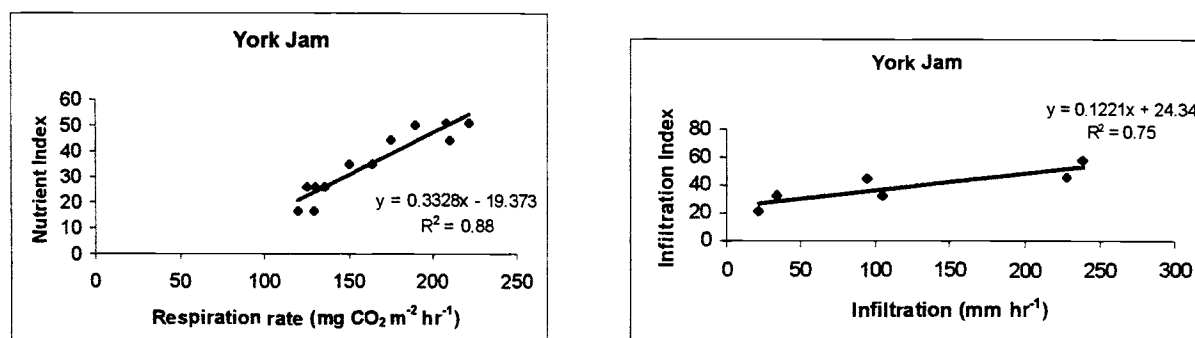


**York Jam** (left chart)
Nutrient Index vs Respiration rate (mg $CO_2$ $m^{-2}$ $hr^{-1}$)
$y = 0.3328x - 19.373$
$R^2 = 0.88$

**York Jam** (right chart)
Infiltration Index vs Infiltration (mm $hr^{-1}$)
$y = 0.1221x + 24.34$
$R^2 = 0.75$

**Figure 1.** Relationships between the LFA indices of nutrient cycling (left) and infiltration (right), and measured soil properties in a york gum (*Eucalyptus loxophleba*) – jam wattle (*Acacia acuminata*) woodland in the Western Australian wheat/sheep zone.

In addition to indicators of soil surface condition, the cover and number of patches, mean obstruction width of patches, and the mean fetch length or distance between patches (Ludwig and Tongway, 2000) have proven useful as indicators of the potential of a landscape to retain resources. 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). There may be a variety of types of both patches and interpatches in a given landscape.

## SCALING-UP LANDSCAPE FUNCTION INDICATORS

At the site level, ground-based methods exist for assessing landscape function (Ludwig et al., 1997) and this methodology has been incorporated into agency monitoring programs (e.g., Karfs et al., 2000). However, there is still the need for the assessment of function at the scale of paddocks, which is the scale important to rangeland managers.

One approach to bridging the scale gap between site and paddock is to use remote sensing techniques. For example, we have recently developed a directional leakiness index (DLI) based on very high resolution remote sensing (e.g., aerial videography; Ludwig et al., 2002). We see this approach as a potentially useful way of indicating landscape function (regulation of resource efficiency) over broader areas. DLI is based on the distance between patch pixels down "columns" of an image (see Ludwig et al., 2002 for formulation and computing details) and index values range between zero (a fully conserving, patch-dominated landscape) and one (totally leaky or dysfunctional). The DLI formulation is "tuned" so that values closely match published data for soil loss versus cover. For example, it is known that resource leakiness (e.g., soil loss) rapidly declines as patch cover (e.g., perennial grass tussocks) increases from very low levels to about 40%, with soil loss little affected at higher ground covers (Scanlan et al., 1996). Testing has shown that the leakiness index positions savanna sites with considerably different patch cover along a continuum of resource conservation that agrees with that obtained using ground data (Ludwig et al., 2002). It has also ranked savanna and arid sites against rated functionality more precisely than other published landscape metrics that would appear to have this capability (Bastin et al., 2002a).

Further development is now required to link the leakiness index with high-resolution satellite data to see if suitably precise estimates of resource conservation can be assessed over larger areas. The 'hyper-spatial'

capacity of currently-available IKONOS imagery is appealing but its 4 m pixel resolution may impose limitations on the ability to discriminate fine-scale vegetation patches. At this pixel size in tussock grassland, patch discrimination will likely be at the level of groups of tussock grasses with many scattered and isolated tussocks being inappropriately classified as interpatches. Where effectively functioning patches are much larger (e.g., mulga groves in central Australia), enlarged pixel size should not be as severely limiting. We need to test how sensitive the leakiness index is when not all patches are adequately discriminated and how critical this may be as index values are integrated across landscapes in a paddock.

The hyperspectral qualities of 'new generation' satellite data (e.g., Hyperion, 228 bands in the spectral range 0.4 to 2.5 mm, see http://eo1.gsfc.nasa.gov/Technology/Hyperion.html) may partly compensate for the limitations imposed by pixel size in adequately discriminating functioning patches in some landscapes. The key requirement will be to suitably 'unmix' patches and interpatches as components of enlarged pixels to see if resultant DLI values better relate to measures of resource conservation (landscape function) obtained by other means.

Our landscape leakiness concept and index (DLI) assumes that flows are approximately in a straight-line direction. This assumption is reasonable for many low-relief landscapes where sheet-flows dominate, e.g., the gentle slopes of semi-arid woodlands in eastern Australia (Ludwig and Tongway, 1995). However, if images include more complex terrain where flows of water are more tortuous or channelised, it would be desirable to include suitably precise digital elevation models with DLI calculations made from satellite imagery. Available contour data generally preclude the generation of locally accurate DEMs and efficient mechanisms have to be developed based on appropriate remotely sensed data (e.g., radar).

It is inevitable during scaling up that the detail of some fine-scale processes will be diminished and perhaps lost. The course we propose could involve undue devaluing of the importance of nutrient cycling in water-limited environments (Adams, this session), particularly on stable soils (e.g., cracking clays) where there are demonstrated links between nutrient accumulation and perennial vegetation. However, we argue that our suggested scaling approach is relevant to many grazed landscapes because of the importance of local redistribution (runoff-runon) and the principle that patch persistence regulates resource supply. Conservation of resources at the patch scale appears to follow through to populations of patches when high resolution remote sensing and the leakiness index are used to rank the functionality of landscapes (Ludwig et al., 2002; Bastin et al., 2002a). Because we cannot distinguish what is present under tree canopies in these remotely sensed data, we may have lost important information about patch quality (e.g., perennial grasses present or absent). Biochemical indices (e.g., nitrogen and lignin content, Serrano et al., 2002) derived from hyperspectral imagery may assist in retrieving some of this information and may also provide useful surrogates of nutrient cycling.

## MODELLING LANDSCAPE FUNCTION PROCESSES AND PREDICTIONS

Another approach to scaling up from site-based process studies to larger-scale landscapes is to use simulation modelling techniques. Progress is being made on developing a spatially-explicit, process-based simulation model of savanna rangelands (Liedloff et al., 2001). A model, called Savanna.Au, uses a grid-based design to simulate the flows of water and soil across landscapes at the scale of a paddock. For example, runoff-runon processes have been modelled as influenced by the condition of soil surfaces (Fig. 2), where the number of runoff events and amount of runoff with large rainfall events is considerably less with good surface condition than with poor condition. Soil surface condition is affected by disturbances such as cattle grazing and fire. The aim of the Savanna.Au model is to predict the outcomes of such disturbances as influenced by different soil types and climatic patterns. For example, simulations have confirmed field studies that suggest that eucalypt savanna rangelands on red loam soils are less resilient to grazing than savanna grasslands on grey clay soils (Ludwig et al., 2001).

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## LEAKINESS IN RELATION TO REDISTRIBUTION

The characteristics of vegetation patches change in different environmental settings and along large environmental gradients. For example, Bastin *et al.* (2002b) reported that patch size and cover decreased and patch separation increased as rainfall decreased from northern to central Australia. Loam sites tended to show greater variation in patch characteristics than sand and clay sites. Although we lack information on water and nutrient relationships, the data provide some inferences about likely redistribution processes. The smaller distances between larger patches on wetter clay sites in northern Australia suggests that there is very limited movement of resources through this landscape and consequently little leakage. In central Australia (near Oodnadatta), patches are very much smaller and further apart on clay soils. They exist because water runs into gilgais that support perennial saltbushes (Atriplex spp.) and Mitchell grass (Astrebla pectinata). Nutrients in any water-borne sediments presumably aid persistence of these perennials. Gilgais retain some of the water within the gibber-strewn and gently sloping landscape but in intense rainfalls, variable amounts flow through (leak) to lower gidyea-lined creeks. Data describing patch size and separation for loam sites also indicate that redistribution is important for their persistence as aridity increases. Sand sites have broadly similar patch characteristics from northern to central Australia suggesting that redistribution is less important, presumably because their high infiltration rates largely preclude surface flows of water and sediment.
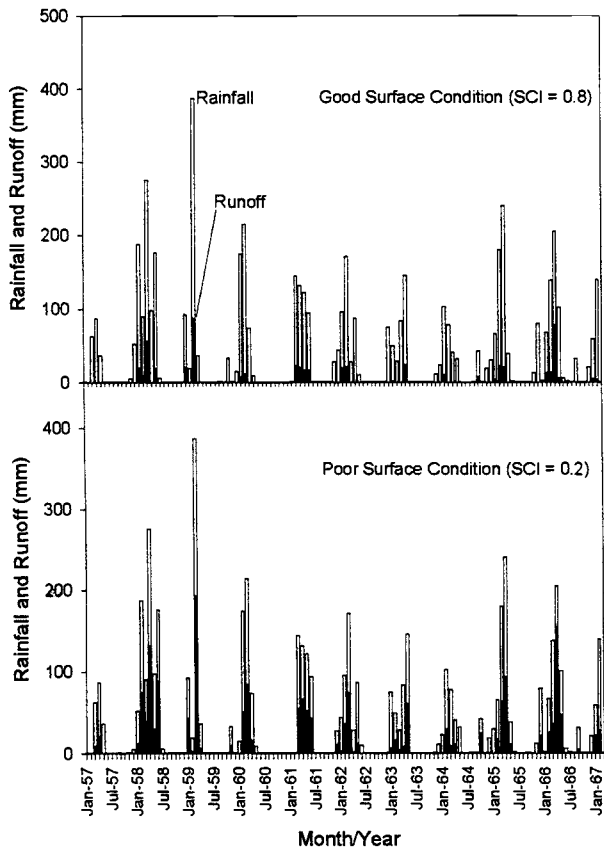


**Figure 2.** Savanna.Au model simulations illustrating how runoff (solid portion of bar) differs for rainfall events over a 10 year period (1957-67) for a savanna landscape with (top) good surface condition (SCI = 0.8) compared to (bottom) poor surface condition (SCI = 0.2). A landscape with good surface condition has fewer and smaller runoff events. The simulated savanna landscape is located on red loam soils in Conkerberry Paddock, Victoria River Research Station, Kidman Springs, Northern Territory.

How then do we accommodate resource movement through landscapes (i.e., leakage) as a component in the analysis of landscape function, particularly in determining grazing impact in landscapes? We need to recognise where and when redistribution between landscapes is a natural process and have a mechanism for filtering its effects during monitoring. One conceptual approach may be through the notion of landscape resilience; that is, do existing monitoring methods (e.g., our leakiness index) provide a useful measure of change in resilience. Resilience is defined in terms of both resistance to disturbance and degree and rate of recovery from a disturbance-induced change (Holling, 1973; Carpenter et al., 2001). In a production sense, we mean change in the capacity of a landscape to produce palatable forage at the scale of paddocks and over a 5-10 year period. Loss of resources (e.g., increased runoff) from one landscape unit may not matter in the medium term if these resources are captured and held by an adjacent unit and the overall net result is increased supply (or stability) of palatable forage. It is difficult to think of examples where this is the case as the reverse situation (resource degradation and loss of resilience) is more likely; e.g., proliferation of inedible woody species in sinks due to increased runoff and deposition of topsoil eroded from adjacent footslopes.

Our leakiness index uses an appropriate reference area to calculate the extent to which resource conservation is reduced due to disturbance and can thus handle the situation where resources are moving through, and potentially being lost from a landscape. A requirement now is to work out the implications of resource transfers between landscapes (as distinct from the patch scale) and the extent to which these matter for landscape resilience.

## LANDSCAPE PATCHINESS AND BIODIVERSITY

Does landscape patchiness and the associated concepts of resource conservation and landscape function provide any useful information about the status of biodiversity? A highly biodiverse landscape should be highly functional while degradation can result in both loss of function and species. In between, there are many possibilities such as retained function and loss of species through, for example, predation. To progress conceptual development in this area, we suggest that initially biodiversity be thought of in terms of providing suitable habitat to maintain viable populations at appropriate spatial and temporal scales. Thus, we would anticipate a relationship between patch obstructions that capture and hold resources and habitat quality specified by security of food and shelter. To better determine the potential role of patch structures, we suggest an analytical structure that may include (and is certainly not limited to) some of the following:

1.  What conditions of resource supply are required for different organisms (at least initially, perennial plants) to occur in different places? For example, can adequate soil water supply be specified statistically (mean, standard deviation, extremes, vertical distribution etc) for different soil textures/types?
2.  When (and how much) is redistribution needed to allow these organisms to persist (prosper) in an environment where otherwise they wouldn't?
3.  What is the functional relationship between degree and frequency of disturbance (by grazing, fire) and amount of landscape still able to support this organism type? Answers here will also need to account for process and rate of recovery from disturbance.

The Biograze work (Landsberg et al., 1997; James et al., 2000) has demonstrated that some plant and animal species are adversely affected by any level of grazing disturbance. Again using distance from water as a surrogate of grazing pressure, Ludwig et al. (1999b) showed how loam and clay soils in northern Australia had different trends in vegetation patch attributes, plant and grasshopper diversity along grazing gradients. Using this type of evidence, we hypothesise that landscape function (resource conservation) and occurrence (persistence) of species could have different functional responses to levels of grazing on different soil types (Fig. 3). These curves are not meant to be definitive; rather, their purpose is to encourage thinking about possible responses of landscape function, habitat quality and species persistence to grazing disturbance on broadly different soil types. The landscape function curves

are analogous to the sigmoidal relationships developed by Graetz and Ludwig (1978) and proposed by Tongway and Hindley (1999) for rangeland monitoring.
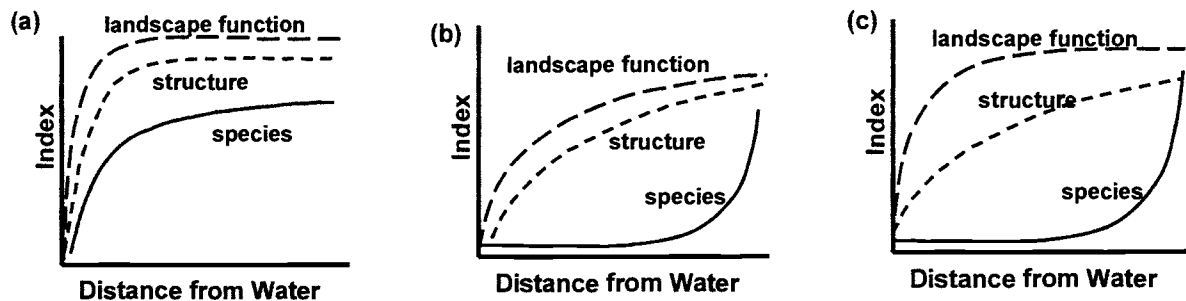


**Figure 3.** Hypothesised change in response of landscape function, vegetation structure (as an indicator of habitat quality) and species with distance from water (as a surrogate of grazing disturbance) on (a) cracking clay, (b) loam and (c) deep sand soils.

Clay soils, and particularly cracking clays, are generally resistant to grazing and altered patch properties leading to reduced conservation of resources would be expected to only extend a short distance from water (Fig. 3a). Where the structure of both soil (e.g., surface cracks, gilgais) and vegetation (density and cover of tussock grasses) provide habitat for fauna, we expect this element of biodiversity value (habitat quality) to show a similar, but slightly less resilient, response to distance from water to that hypothesised for landscape function. The structure curve lies below the landscape function curve because (1) trampling breaks down soil structure collapsing gilgais and filling surface cracks and (2) grazing reduces cover of tussock grasses. Provided gilgais and tussocks (patches) persist, vegetation structure (and habitat quality) should be maintained. However, patch cover will vary with rainfall and level of defoliation.

There is evidence that some plant species occurring on loam soils are much more vulnerable to grazing disturbance in that they are only found in water-remote locations (James et al., 2000; Fig. 3b). Using the data of Ludwig et al. (1999b), we expect that increased landscape leakiness will propagate further from water than is the case on cracking clay soils due to both loss of palatable perennial vegetation and altered soil properties. Vegetation structure will likely show a variable response to long term grazing across the loam soils of Australia's rangelands. However, because trees and shrubs are an important component of patches on many loams, index values of habitat quality could mirror those of landscape function (resource conservation) in some situations where grazing is the principle cause of disturbance. Different response shapes will likely occur with shrub encroachment or where fire has removed much of the woody layer. Functional responses are more tentative for sands because of even greater lack of data. In Fig. 3c we suggest that the response shapes on deep sands in central Australia (hummock grasslands) may be similar to those defined for loam soils. That is, a small number of species are adversely affected by any grazing while landscape function is relatively unaffected. Vegetation structure is more sensitive to grazing disturbance. Fire is a further disturbing influence and may interact with grazing to alter the shape of the structure and species curves.

As stated previously, our intention is not to specify definitive response shapes but to argue that the ability to define continuous functional relationships between the degree of disturbance (grazing in Fig. 3) and the amount of landscape still able to support an organism type may provide insights into aspects of monitoring and managing biodiversity. Where functional responses are aligned, then the nature of vegetation patches (and implied degree of resource conservation) may provide a suitable surrogate of attributes aligned with biodiversity, and methods like the leakiness index a suitable means for monitoring its status.

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