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Monitoring ecological indicators of rangeland functional integrity and their relation to biodiversity at local to regional scales

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Abstract Functional integrity is the intactness of soil and native vegetation patterns and the processes that maintain these patterns. In Australia's rangelands, the integrity of these patterns and processes have been modified by clearing, grazing and fire. Intuitively, biodiversity should be strongly related to functional integrity; that is, landscapes with high functional integrity should maintain biodiversity, and altered, less functional landscapes may lose some biodiversity, defined here as the variety and abundance of the plants, animals and microorganisms of concern. Simple indicators of biodiversity and functional integrity are needed that can be monitored at a range of scales, from fine to coarse. In the present paper, we use examples, primarily from published work on Australia's rangeland, to document that at finer patch and hillslope scales several indicators of landscape functional integrity have been identified. These indicators, based on the quantity and quality of vegetation patches and interpatch zones, are related to biodiversity. For example, a decrease in the cover and width (quantity) and condition (quality) of vegetation patches, and an increase in bare soil (quantity of interpatch) near cattle watering points in a paddock are significantly related to declines in plant and grasshopper diversity. These vegetation patch-cover and bare-soil indicators have been monitored traditionally by field-based methods, but new high-resolution, remote-sensing imagery can be used in specific rangeland areas for this fine-scale monitoring. At intermediate paddock and small watershed scales, indicators that can be derived from medium-resolution remote-sensing are also needed for efficient monitoring of rangeland condition (i.e. functional integrity) and biodiversity. For example, 30–100-m-pixel Landsat imagery has been used to assess the condition of rangelands along grazing gradients extending from watering-points. The variety and abundance of key taxa have been related to these gradients (the Biograze project). At still larger region and catchment scales, indicators of rangeland functional integrity can also be monitored by coarse-resolution remote-sensing and related to biodiversity. For example, the extent and greenness (condition) of different regional landscapes have been monitored with 1-km-pixel satellite imagery. This regional information becomes more valuable when it indicates differences as a result of land management. Finally, we discuss potential future developments that could improve proposed indicators of landscape functional integrity and biodiversity, thereby improving our ability to monitor rangelands effectively.

Key words: biodiversity, landscape function, landscape integrity, monitoring, rangeland, remote-sensing.

INTRODUCTION

The rangelands of Australia are vast, covering 6 million km^2, and are highly complex, with climate, vegetation, soil and biota varying greatly across the continent (Harrington *et al.* 1984). These rangelands, defined as those landscapes where the primary use is pastoral, have been classified into bioregions that vary in their likely value for pastoral use and their likely susceptibility to damage by this use (Stafford Smith *et al.* 2000; Smyth *et al.* 2003). This pastoral damage takes many forms, but one impact is the loss of landscape functional integrity, which is the intactness of natural vegetation and soil structural patterns and the processes that maintain these patterns. This loss of landscape functional integrity, including the shelter and food provided by vegetation, is a likely cause of known extinctions and reported declines in native herbaceous plants, small mammals and granivorous birds in rangeland bioregions (Woinarski 1999). However, these losses in functional integrity, and hence in biodiversity, have occurred at different spatial scales, from local hillslopes to regional catchments. We need to understand better these scale-dependent relationships between losses in functional integrity and losses in biodiversity, defined here as the variety and abundance of the plants, animals and microorganisms of concern.

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Is there evidence that a loss of functional integrity at a local landscape (patch-hillslope) scale leads to a loss of biodiversity at this scale? Is there similar evidence at coarser paddock, watershed and regional catchment scales?

As stated in a definition of savannah health by Whitehead *et al.* 2000, basic landscape patterns and processes need to be maintained at all spatial scales, from fine to coarse. That is, healthy landscapes retain water, soils, nutrients and organic matter in a network of patches on hillslopes within paddocks, within watersheds on properties, and within regional catchments. In the present paper, we define landscapes as being composed of two or more land units positioned so that they are functionally linked by source–sink processes (e.g. run-off–run-on), which can vary from finer hillslope scales (e.g. a catenary or toposequence) to coarser watershed scales (e.g. a catchment; Forman & Godron 1986), and we use the term hillslope to refer to gently inclined landforms that are dominated by sheetflows and that extend from ridgelines to creek lines (see McDonald *et al.* (1990) for a full list of hillslope categories). Of course, during large rainfall events there are natural flows of water and materials down hillslopes and out of catchments, but there is concern when these flows off hillslopes and down watersheds become excessive as a result of unhealthy landscapes, especially if they extend over large areas (Cramer & Hobbs 2002; Prosser *et al.* 2002). In addition, in this definition of landscape health, populations of plants and animals need to be maintained at appropriate spatial and temporal scales. That is, it is generally accepted that it is achievable to maintain a high diversity of habitats and populations only over longer time frames at coarser regional scales. Therefore, we need to improve our understanding of the links between landscape function (integrity of patterns–processes) and biotic populations over a hierarchy of scales, from hillslope patches to regional catchments. We need to know what landscape attributes are intact and emerge at the finer scales that are important for broader-scale management and reporting applications in rangelands.

Directly measuring the functional integrity of landscapes, for example quantifying the retention of water and nutrients on hillslopes by patches, is very time-consuming and costly (Herrick & Wander 1998; Valentin *et al.* 1999). Therefore, simple indicators of landscape integrity are required for monitoring the state of health or functionality of a rangeland (Tongway & Ludwig 1997). We define an indicator as an easily acquired measure that relates to a basic process of landscape function (i.e. a surrogate). Useful indicators are sensitive to change, are convenient and inexpensive to apply by a range of operators after appropriate training, and are capable of providing a predictive understanding of landscape function when used with an appropriate conceptual, monitoring framework (Tongway & Hindley 2000; Smyth *et al.* 2003).

Here, we look specifically for indicators of those attributes of functional integrity that link to biodiversity across spatial scales. Although there are a few general examples and frameworks that document links between ecological integrity and biodiversity (Schulze & Mooney 1993; Sanderson 2002), specific rangeland examples are rare.

In the present paper, we explore the Australian rangeland literature for the following: (i) examples of attributes and indicators that relate landscape functional integrity to biodiversity from patch-hillslope to regional catchment scales; and (ii) attributes and indicators useful at finer spatial scales that emerge and feed into broader-scale management and monitoring applications. The focus of the present paper is largely on spatial, not temporal relationships between functional integrity and biodiversity. We appreciate that these relationships across time scales are also very important, but the documentation and analysis of such temporal dynamics with, for example, simulation models are beyond the scope of the present paper.

FUNCTIONALITY AND BIODIVERSITY: PATCH-HILLSLOPE SCALES

We began with an example of how vegetation patches act to obstruct flows on a hillslope. These patches have a richer and more productive composition of plants than open areas surrounding them. A high cover of vegetation patches that obstruct flows indicates a landscape with a high functionality. We then compared the loss of this functionality with the habitat favourability for woodland hillslopes cleared for grazing use in rangelands. We also compared two other hillslopes, one within an exclosure and the other near a watering-point, to illustrate how landscape functional integrity and biodiversity are related.

Log mounds as patch obstructions on hillslopes in mulga woodlands

In the extensive mulga woodlands used as rangelands in Australia (Harrington *et al.* 1984), dead mulga trees (*Acacia aneura*) often fall across hillslopes, not only obstructing the flows of run-off down these hillslopes, but also trapping wind-blown sediments to form a soil hummock around the fallen logs. These log–soil mounds represent obstructive patches in these landscapes, and evidence suggests that they strongly affect water-transfer processes (Tongway *et al.* 1989). For example, five mulga log mounds had consistently higher infiltration rates (60–228 mm h^{-1}) than soils

3-m upslope of these mounds (15–29 mm h^{-1}). Soils from log mounds also had significantly greater quantities of organic carbon and nitrogen than soils 3-m upslope ($P < 0.05$). Importantly, we observed that these 'fertile patches' had a greater variety of plant species and they had a significantly greater biomass production (mean ± standard error (SE), 10.6 ± 2.9 g m^{-2}) than open slopes around these log mounds (0.9 ± 0.6 g m^{-2}). The role of how fine-scale mulga logs affect landscape processes and plant variety and production subsequently emerged as a useful link for restoring the functional integrity of degraded rangelands (Ludwig & Tongway 1996; Tongway & Ludwig 1996), which can be applied at larger paddock scales (Noble *et al.* 1997).

Tall tussocks as obstructions on hillslopes in cleared eucalypt woodlands

Many landscapes in the grassy eucalypt woodlands of subhumid to temperate eastern Australia have been partially or totally cleared for use as native or exotic pastures with documented impacts on biodiversity (McIvor 1998; Fairfax & Fensham 2000; Franks 2002). For example, near Crows Nest in south-eastern Queensland, pastures in eucalypt woodlands are positioned on a continuum of clearing and grazing intensity from intact, lightly grazed hillslopes to cleared, heavily grazed hillslopes (Fig. 1; Tongway & Hindley 2002). Six sites, which occur on similar soils and hillslopes in the Crows Nest study area, define the six positions of landscape functionality along this continuum. However, for brevity and emphasis, we only compared position 1 with position 6.

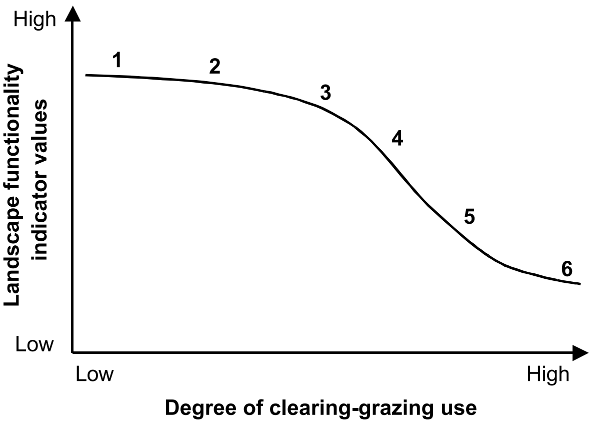
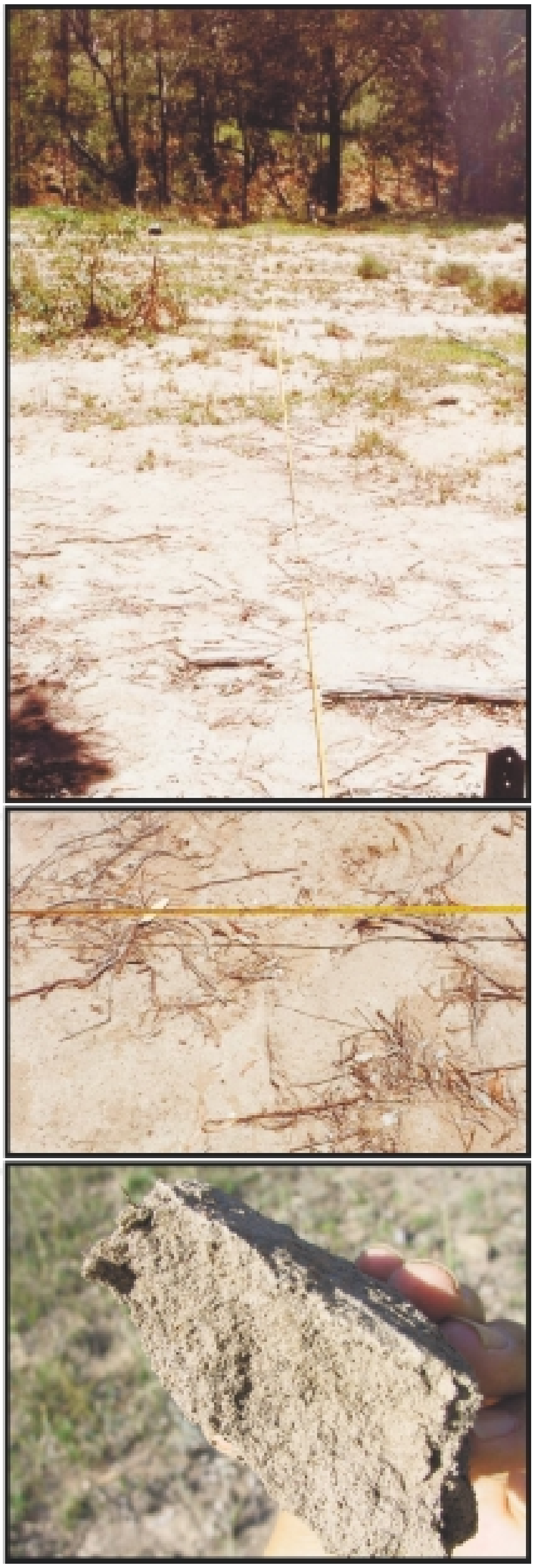


Fig. 1. A relative positioning of six sites along a continuum from low to high landscape disturbance based on indicators of landscape functionality.

Fig. 2. Photographs of the Crows Nest site with high landscape functionality indicators (position 1 in Fig. 1) illustrating (a) the landscape dominated by trees and large perennial tussock grasses, (b) the complex litter structure on the landscape surface, and (c) the soil under a tussock with crumb structure and an open fabric.

Based on standard landscape function analysis indicators (Tongway & Hindley 2000), the Crows Nest site located at position 1 (Fig. 1) had relatively high functionality indicator values for surface stability, infiltration capacity and nutrient cycling potential (Tongway & Hindley 2002). Trees and large perennial tussock grasses dominated the site (Fig. 2a). The landscape surface was also protected by a complex litter structure (Fig. 2b). In combination with plants, this litter prevented raindrops from impacting on the soil surface. The soil under the tussocks had a crumb structure and an open, friable fabric with large biopores (Fig. 2c). This porosity was a result of the presence of soil-dwelling fauna such as earthworms, ants and termites (Eldridge & Greene 1994). There was no evidence of major resource (water and soil) loss from this hillslope. Obviously, rainwater would trickle slowly through the dense grass and litter, but its transporting capacity would be very low, except possibly for transporting dissolved chemicals.

(a)
(b)
(c)



The Crows Nest site at position 6 (Fig. 1) had relatively low functionality indicators for surface stability, infiltration capacity and nutrient cycling potential (Tongway & Hindley 2002). Trees had been cleared to the creek line (Fig. 3a) and grazing had greatly reduced ground cover (Fig. 3b). The soil was massive and crusted with little porosity (Fig. 3c), which is typical of soils where vegetation has been substantially reduced by grazing (Greene 1992). No biological residues were visible and soil fauna such as earthworms were unlikely to occupy this poor quality site as a result of its hardness and lack of organic substrate. Although these soils retained quite a bit of residual stability because of their innate soil coherence, any mechanical disturbance (e.g. trampling) of the soil surface would lead to erosion as the brittle surface is powdered, so it easily washes away. In fact, active, head-cutting gullies were observed on this site (Tongway & Hindley 2002), potentially leading to a massive loss of resources from this landscape system.

Comparing the biodiversity attributes and indicators for position 1, with its high functional integrity, with the low functional integrity of position 6 illustrated how these landscape properties were related (Tongway & Hindley 2002). It was observed that the highly functional position 1 had a rich variety of perennial grasses with a high density (109 plants m^{-2}) and basal area (1763 cm^2 m^{-2}), whereas position 6 had, on average, only three perennial grasses m^{-2}, with a low basal area (16 cm^2 m^{-2}). Furthermore, site observations on diggings and dung indicated that the abundance of bettongs and bandicoots was much greater at position 1 than at position 6.

Fig. 3. Photographs of the Crows Nest site with low landscape functionality indicators (position 6 in Fig. 1) illustrating (a) the landscape with trees cleared to the creek line, (b) a greatly reduced ground cover, and (c) the soil with a massive and crusted structure.

Tall tussocks as obstructions on hillslopes in tropical savannahs

In the vast tropical savannahs extending across northern Australia (Harrington *et al.* 1984), the natural ground-layer is typically tall, perennial tussock grasses such as *Dichanthium* and *Heteropogon* spp. If tree clearing and intensive grazing by feral animals and livestock alter this ground-layer, run-off–run-on processes and the abundance of birds, reptiles and small mammals are impacted (Ludwig & Tongway 2002). On a site in the Victoria River District where grazing was excluded for 27 years, landscape functionality was high, as indicated by a ground-layer patch cover of 58% and a total width of patches as obstructions of 88 m along a 100-m transect (Ludwig *et al.* 1999), compared with a patch cover of only 16% and an obstruction width of only 18 m per 100 m on a nearby site located close to a watering point where cattle impacts were relatively greater. Near this watering point, the richness of plant species and grasshoppers was also lower (four plant spp. per 10 m^2 and three grasshopper spp. per 2500 m^2) compared with the stock exclusion site (eight plant spp. per 10 m^2 and eight grasshopper spp. per 2500 m^2).

These two sites in the Victoria River District, representing opposite ends of a gradient of landscape functionality, were also used to verify a leakiness index derived from remote-sensing data for these sites (Ludwig *et al.* 2002). This index can be used to indicate the potential for a landscape to retain, rather than leak resources such as rainwater and soil. Although this landscape leakiness index is most strongly related to patch cover, it is also related to patch number, size, shape and spatial arrangement and orientation. It compares favourably with other landscape spatial metrics such as the lacunarity index, which measures the size and arrangement of gaps in a spatial map (Bastin *et al.* 2002a). This leakiness index can be used for hillslopes in landscapes, such as many rangelands, where vegetation patches can be detected by remote-sensing and classified into patches (pixels) that obstruct sheetflows and into non-patch areas that are open and relatively non-obstructing (e.g. areas of bare soil).

FUNCTIONALITY AND BIODIVERSITY: SMALL WATERSHED SCALES

When viewing and studying small watersheds within paddocks on properties in rangelands, most of the run-off from a rainstorm event will flow down hillslopes and drainage-lines to larger run-on zones such as riparian bands along creeks. These bands can serve as important 'filters' for soil sediments and organic materials being washed off adjacent hillslopes (Karssies & Prosser 2001). At this scale, erosion–deposition transfer processes form distinct landscape patterns that have been described as 'erosion cells' (Pickup 1985). Erosion cells also exist on flatter landscapes, where sediment movement is more subtle and source–sink zones may only be connected following large rains, but here we demonstrate the development of relationships between functionality and biodiversity on steeper landscapes at the scale of small watersheds.

Large rangeland paddocks (i.e. >10 km in length or width) may contain one or more of these erosion-cell patterns (Pickup & Chewings 1986) and one or more artificial watering-points for livestock (Landsberg *et al.* 1999). Distance from watering-points was used as a surrogate for grazing intensity in the Biograze project (James & Fisher 2000; James *et al.* 2000), where grazing affected landscape functionality and the variety and abundance of key flora and fauna taxa such as reptiles, birds, small mammals and ants. This Biograze project documented those taxa that benefited from grazing disturbances that reduced landscape functionality (i.e. taxa that increase near water, such as the short-lived herb bogan flea, *Calotis hispidula*, and the brown songlark, *Cinclorhamphus cruralis*); those taxa that strongly decreased with grazing-induced losses in landscape functionality near water (e.g. the desert daisy *Vittadinia eremaea*, and the hooded robin, *Melanodryas cucullata*); and those taxa that did not significantly respond to grazing disturbances and changes in landscape functionality. These findings confirmed findings from other grazing gradient studies that suggest that understorey plants and birds are more efficient indicators of grazing impacts than invertebrates (Landsberg *et al.* 1999).

The condition of the vegetation in paddocks, and trends in this condition over time with proximity to watering-points have been detected by medium-resolution remote-sensing since the late 1980s and early 1990s (e.g. Landsat MSS resampled to 100-m pixels; Pickup *et al.* 1994, 1998). More recently, these patterns in rangeland condition have been monitored using high-resolution remote-sensing and related to ground-based landscape function and biodiversity indicators (Bastin *et al.* 2002b). For example, the Biograze project was located in the Kingoonya region of north-west South Australia. In the study, the mean spacing, or fetch length, between bluebushes *Maireana sedifolia*, was 5.5 m at 150 m from the watering-point in Digitalis paddock on Mobella Station, but bluebush spacing was closer (approximately 2 m) beyond 1 km from water (Kinloch *et al.* 2000). This fetch length indicates how far a soil or litter particle would flow in run-off or blow in winds before striking a bluebush obstruction. Obviously, the closer the spacing of bluebushes, the less likely it is that resources will leak from the landscape. The spacing between bluebushes also reflects vegetation integrity or habitat structure, which probably influences the occurrence and abundance of fauna, such as the brown songlark and hooded robin.

Using Landsat multi-spectral scanner (MSS) and Landsat Thematic Mapper (TM) satellite imagery and ground-based measurements taken in paddocks from 1994 to 2002 on a set of landscape function indicators

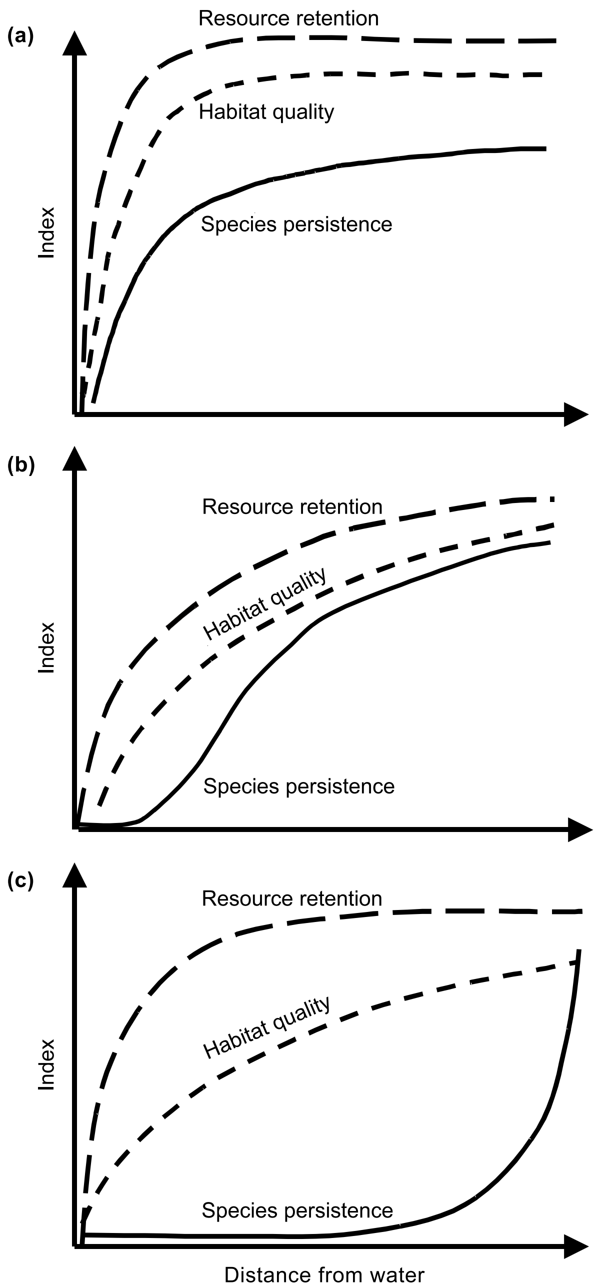


Fig. 4. Hypothesized change in response of resource retention, habitat quality and the persistence of grazing-sensitive species with distance from water (as a surrogate of grazing disturbance) on (a) cracking clay, (b) loam, and (c) deep sand soils.

(Karfs 2002), 45 rangeland sites in the Victoria River District were ranked along a continuum from good to poor condition. The relationship between land condition and biodiversity status was explored (Karfs & Fisher 2002). In general, rangelands in poor condition had lower abundances of plants, birds, small mammals, reptiles and ants than sites in good condition. These 45 sites were on calcareous loam soils with eucalypt savannah vegetation.

At the patch-hillslope and paddock-watershed scales, relationships between landscape functional integrity and biodiversity clearly varied by soil type. For example, loam and clay sites in northern Australia had different trends in vegetation patch attributes and plant, ant and grasshopper diversity with distance from water (Ludwig *et al.* 1999; Hoffmann 2000), where, again, this distance was used as a surrogate for grazing intensity.

Based on these studies and on other observations (Pringle 2002a), we hypothesized that landscape function (as potential to retain resources), habitat quality (as intact vegetation or landscape structures providing food and shelter) and species persistence (occurrence and abundance) were likely to have different responses to different levels of grazing (as distance from water) on different soil types (Fig. 4). These three response curves were specifically for species sensitive to grazing disturbances (decreasers) and were not meant to be definitive; rather, their purpose was to encourage thinking about possible responses of resource retention, habitat quality and the persistence of grazing-sensitive species for broadly different soil types. The aim was to expand on the decreaser, increaser and neutral species' responses found with distance from water, largely for loamy soils, by the Biograze project (James & Fisher 2000; James *et al.* 2000).

Note that, for the species response curves for clay, loam and sand soil types (Fig. 4), the resource retention and habitat quality curves were approximately parallel. We did this to imply the strong relationship between indicators of landscape functional integrity, such as the width of patch obstructions across a hillslope that capture and retain resources, and indicators of habitat quality, such as how the cover of these patches provides food and shelter for animals. We suggested that indicators of habitat quality could, in turn, be thought of as indicators of biodiversity; that is, habitat quality is a surrogate for biodiversity potential (species persistence).

For example, clay soils, particularly cracking clays, are generally more resistant to grazing and altered patch properties (Ludwig *et al.* 1999; Pringle 2002a), and reduced ability to retain resources and loss of grazing-sensitive species is expected to extend only a short distance from water (Fig. 4a). Where the structure of both soil (e.g. surface cracks, gilgais) and vegetation (density and cover of tussock grasses) provided habitat for fauna, we expected this indicator of biodiversity value (habitat quality) to show a similar, but slightly less resilient response to distance from water to that hypothesized for resource retention. In other words, the habitat quality curve was below the resource retention curve on clays because (i) trampling breaks down soil structure, collapsing gilgais and filling surface cracks; and (ii) grazing reduces cover of tussock grasses.

In contrast, loam soils are much more vulnerable to grazing disturbance, and grazing-sensitive species are likely to be lost near water but will persist away from water (Fig. 4b). This sigmoid response is commonly observed in rangelands with loamy soils (Graetz & Ludwig 1978; James *et al.* 2000). Because trees and shrubs are an important component of vegetation patches on many loams in rangelands, index values for habitat quality are likely to track those of resource retention (Fig. 4b). However, different response shapes are likely to occur with shrub encroachment or where fire has removed much of the woody layer.

Functional responses are somewhat tentative for sands because of lack of example data. It is known that rates of water and nutrient movement are quite resilient to cattle grazing in the deep sands of the eastern Kalahari, Africa (Dougill *et al.* 1998). In central Australia, deep sands support largely unpalatable hummock grasslands that are minimally grazed. Here, we suggested that the response shape for resource retention may be similar to those for clay soils; that is, relatively unaffected (Fig. 4c). We also suggested that habitat quality and species persistence may be more sensitive; that is, the few palatable species might be highly selected and might only be found well away from water.

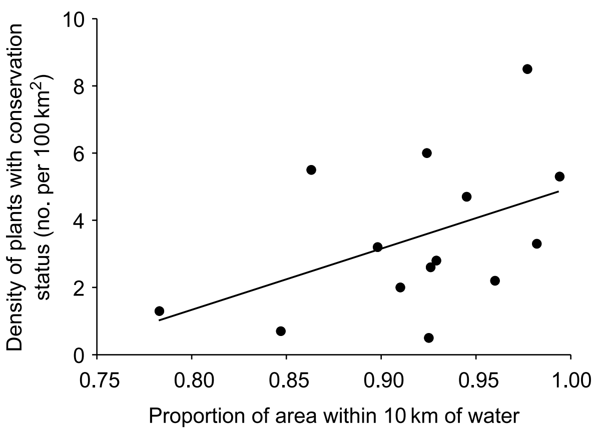


Fig. 5. The density of plant species with declared conservation status in 14 rangeland types in relation to the area within each type that is within 10 km of water expressed as a proportion of its total area (e.g. values close to 1 indicate that most of the area is within 10 km of water).

FUNCTIONALITY AND BIODIVERSITY: CATCHMENT SCALES

At the catchment scale, region-wide storms such as tropical rain depressions from cyclones can cause major floods, such as those that have occurred in the Burdekin River, Queensland (Prosser *et al.* 2002). At this coarse scale, lowlands, wetlands and floodplains capture and retain many of the resources that flow from upland watersheds and hillslopes during and following these storm events. Furthermore, region-wide 'greening-up' is observed, as reflected in remotely sensed greenness indices, such as the normalised difference vegetation index (NDVI) (Cridland & Fitzgerald 2001) and green cover changes (Karfs *et al.* 2000).

A regional case study on rangeland condition and biodiversity was conducted as part of the National Land and Water Resources Audit (Bastin & James 2000). This study covered 16 pastoral leases in the southern end of the Northern Territory, Australia, and built on earlier published results of land degradation based on analysis of Landsat MSS data (Bastin *et al.* 1993). Degradation was defined as 'a grazing-induced reduction in the amount of vegetation cover likely to be present after the best growth conditions experienced within a reasonable time'. In this Audit case-study region, the more productive landscapes were more intensively developed, with infrastructure (fences and watering-points) for grazing, than the pastorally less useful country and showed greater evidence of degradation. Species that were intolerant of higher grazing impacts were predominantly found at distances well away from water, which was present in a low proportion of the landscape. These water-remote areas or patches were dispersed and fragmented; however, they were very important refugia for such grazing intolerant species (James & Fisher 2000).

In the Audit case-study region, the persistence of species that were negatively affected by grazing was explored (Bastin & James 2000). This was done by examining the relationship between the number of plant species that had conservation significance and the degree of rangeland degradation and fragmentation, with the latter defined as the area within 10 km of water, expressed as a proportion of the total area. The analysis was restricted to 14 of the more productive rangeland types (Fig. 5). Although this linear relationship was relatively weak ($r^2 = 0.21$) and was only significant at $P < 0.10$ (and thus any conclusions must be viewed cautiously), it did suggest that plant assemblages of the more productive rangelands tended to have higher numbers of species of conservation significance. That is, the number of threatened plant species (i.e. those with recognized conservation status) found per 100 km^2 in each of the 14 more productive rangeland types increased as the development of a water-point increased.

This tenuous finding needs to be confirmed for other rangeland regions, such as the Gascoyne–Murchison in Western Australia (Pringle 2002b), to verify that it is not an artefact of the natural plant assemblages that occur within the Audit case-study region in the southern Northern Territory (Bastin & James 2000). If valid, this simple index based on distance from water and state of degradation (obtained from satellite data in extensively grazed areas) could have value as a regional-scale indicator of biodiversity threat in rangelands, and could help target on-ground monitoring toward areas and indicator taxa (or focal species; Lambeck *et al.* 2000) that provide the most critical assessment of regional-scale biodiversity integrity. In other words, for more productive rangeland landscapes, the proportion of the area within a threshold distance of water (e.g. 10 km) could be used to indicate the likely persistence of threatened plant species. Furthermore, we expect that the remote-sensing procedures applied in the Audit case study would be transferable to other rangeland regions where land degradation is expressed through incomplete vegetation recovery in the vicinity of water following major rainfall events.

Case studies at the catchment scale, such as at Gascoyne–Murchison, suggest that a cooperative programme involving rangeland managers and government agency staff may deliver the best environmental management outcomes (Pringle 2002b). One of the aims of this Gascoyne–Murchison catchment programme is to bridge the communication gap between resource managers on the land and the government, so that policies and legislation produce desired outcomes: the conservation of specific biodiversity values and the ecologically sustainable management of rangelands in the catchment (Pringle & Tinley 2001).

DISCUSSION

Emerging indicators of landscape functional integrity and biodiversity

Our examination of Australian rangeland published reports reveals a number of examples illustrating how biodiversity is related to the functional integrity of landscapes at local patch to regional catchment scales. Over this range of scales, two indicators of landscape functional integrity emerged from fine-scale patch-hillslope studies that appear to be important to the variety and abundance of biotic populations at this scale, and have emergent properties; that is, they translate to coarser watershed and catchment scales. These two indicators are vegetation patch quantity and quality, which reflect the potential of a landscape to retain, not leak, vital water and nutrient resources. Vegetation patch quantity and quality, as surrogates for resource retention, can be simply measured by the cover (intactness) and condition (quality) of vegetation patches and zones. For example, local hillslopes with a high ground cover of large, robust vegetation patches in good condition have a richer variety and greater abundance of plants and animals than hillslopes where these patches have been reduced by disturbances (Tongway & Hindley 2002). The cover and condition of vegetation patches can be monitored by ground-based and high-resolution remote-based techniques (Ludwig *et al.* 2000; Karfs 2002). At watershed scales, these patch indicators are now viewed as bands of vegetation along drainage-lines and riparian zones along creeks, and the intactness and condition of these larger patch patterns indicate the potential for landscapes to retain resources and provide quality habitats at this coarser scale. These patterns can be monitored using medium-resolution remote-sensing techniques (e.g. Landsat MSS and TM; Pickup *et al.* 1994; Bastin *et al.* 1998).

At regional scales, more intensively grazed landscapes have reduced vegetation cover, including perennials, close to watering points. This infers reduced biodiversity. These landscapes are also more likely to have more species under threat within the area (Bastin & James 2000). Also at regional catchment scales, landscape patches can be viewed as the wetlands and lowlands that capture flows and filter resources from upland watersheds and hillslopes. Again, the intactness (cover, quantity) and greenness (quality) of these regionally important vegetation patches indicate the capacity of the regional landscape to retain resources and provide habitat. These vegetation cover and greenness indicators can be monitored at short time intervals by relatively cheap, coarse-resolution remote-sensing techniques (e.g. NOAA AVHRR imagery; Cridland & Fitzgerald 2001). Thus, the functional integrity of landscapes, particularly the cover and condition of vegetation patches, which provide habitats for a variety of organisms, is an important indicator to monitor in rangelands and, fortunately, this indicator can be measured by remote-sensing.

Advances in remotely sensing landscape integrity

Ground-based measurements of landscape integrity, using a procedure called landscape function analysis (LFA; Tongway & Hindley 2000), are now an established part of many agency rangeland monitoring programmes (Karfs *et al.* 2000). LFA closely examines the condition of vegetation–soil surfaces (patch quality), and it measures the cover and number of perennial vegetation patches (quantity). The mean obstruction width of these patches and the mean fetch length or distance between patches are also useful indicators of the potential of Australian rangeland landscapes to retain resources (Tongway & Ludwig 1997; Ludwig & Tongway 2000). Although there remains a need to continue this ground-based monitoring of indicators of landscape integrity, there is also a need to assess landscape integrity at the scale of the watershed and paddock, which is the scale important to many rangeland managers. Information is also needed at the larger catchment scale where these landscape integrity and biodiversity indicators are required for regional and national reporting (Williams *et al.* 2001).

In addition to simple vegetation-patch-size cover and soil-surface-condition indicators of landscape functional integrity, the arrangement of vegetation patches within a landscape is also important for how well resources are potentially retained, and a simple resource retention or leakiness index, based on high-resolution, remotely sensed imagery, has been developed (Ludwig *et al.* 2002). We see this remotely sensed leakiness index as a useful way of indicating resource regulation over broad areas (Bastin *et al.* 2002a). However, further development is required to link the leakiness index with high-resolution satellite data to see if suitably precise estimates of resource retention can be assessed over larger areas.

The hyper-spatial capacity of currently available Ikonos and Quickbird imagery is appealing for quantifying landscape patchiness and integrity. However, even their 1–4-m-pixel resolution may be insufficient for discriminating fine-scale patches in certain vegetation types. For example, at these pixel sizes in tussock grasslands, patch discrimination will likely be at the level of groups of grass tussocks (clumps), with scattered and isolated tussocks being inappropriately classified as open interpatches. Where effectively functioning patches are much larger (e.g. mulga groves in central Australia), larger pixel sizes should not be as limiting. However, 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 within a paddock.

The hyper-spectral qualities of new generation satellite data (e.g. Hyperion, 220 bands in the spectral range 0.4–2.5 μm) may partly compensate for the limitations imposed by the larger (e.g. 30-m) pixel size of more conventional Landsat MSS and TM imagery. The key requirement will be to 'unmix' spectral signatures suitably for patches and interpatches as components of enlarged pixels; this may be difficult. The aim would be to see if the leakiness values obtained by these data would be better related to measures of resource retention (landscape function) obtained by other means. However, because remotely sensed imagery cannot distinguish what is present under tree canopies, some important information about patch quality (e.g. perennial grasses present or absent) may be lost.

Our landscape leakiness concept and index assumes that resource flows are approximately unidirectional. This assumption is reasonable for many low-relief landscapes where sheetflows dominate (e.g. the gentle slopes of semiarid woodlands in eastern Australia; Ludwig & Tongway 1995). However, if images include more complex terrain where flows of water are more tortuous or channelized, it would be desirable to combine suitably precise digital elevation models with satellite imagery (Pickup & Chewings 1996) and then calculate leakiness from this combined data; this has not been done. Available contour data generally preclude the generation of locally accurate digital elevation models, and efficient mechanisms have to be developed based on appropriate remotely sensed data (e.g. radar or multi-angle scanning of advanced spaceborne thermal emission and reflection (ASTER) radiometer imagery).

We recognize that resource retention or conservation may seem less important in defining landscape integrity in some rangeland environments, or its relevance may appear disguised. Examples include tussock grasslands on flat cracking-clay soils, and temperate and subtropical grassy woodlands with annual rainfall in excess of approximately 600 mm. These areas may have grassy-sward ground layers where patchiness is very fine-scaled, hence not apparent, and where resource retention is less affected by grass-butt size and crown separation or distance. Nevertheless, the basic principle of resource regulation holds at these and at much higher rainfall regimes, because all plants provide organic substrates that stabilize soil aggregates, hence improving infiltration and reducing erosion (Oades 1984, 1993). We also recognize the importance of nutrient cycling in maintaining plant production, evident at a within-patch scale (Adams 2002), and across rangeland regions (visible as greenness in imagery; Cridland & Fitzgerald 2001). Both water redistribution through run-off and run-on and nutrient conservation and utilization are vital for maintaining biophysically functioning landscapes that are rich in habitat quality and populations of organisms.

Advances in landscape functionality and rangeland restoration

Rangelands can be restored by building vegetation patches that function to retain resources on hillslopes or at the base of hillslopes (Purvis 1986; Bastin 1991; Tongway & Ludwig 1996; Noble *et al.* 1997; Karssies & Prosser 2001). However, when restoring many rangelands, a broader landscape view is needed – a view that encompasses geomorphic and hydrological processes. For example, building on earlier erosion cell concepts (Pickup 1985), a hierarchical geo-ecological view is being advanced as an approach to restoring and managing rangelands in Western Australia (Pringle & Tinley 2001; Pringle 2002b). Basically, this approach assesses key geomorphic processes within a drainage basin. It aims to identify and treat incision 'nickpoints' in the landscape where disturbances have caused head-cutting gullies that literally 'pull the plug', diverting water from landscape surfaces. These altered water regimes can cause vegetation changes over large landscape areas in the basin (e.g. shrub encroachment). This altered vegetation is likely to persist unless incision nickpoints are repaired to restore former geomorphic and hydrological processes and patterns. The ecological consequences of these subtle alterations in eco-hydrological processes are now being studied in rangelands of Australia at hillslope (Prosser *et al.* 2001; Dunkerley 2002; Ludwig & Tongway 2002), watershed (Cramer & Hobbs 2002) and catchment scales (Pickup & Marks 2000; Prosser *et al.* 2002). Practical applications to repair hydrological processes in rangelands include progressively building retention banks down hillslopes (Purvis 1986), and the Ecosystem Management Unit process (Pringle & Tinley 2001).

Future developments in relating landscape functionality and biodiversity

In the present paper we explored landscape functionality, as defined by resource retention, and the integrity of landscape structure, as defined by patchiness, and whether these concepts provide useful indicators and information about the status of biodiversity. We used Australian rangeland examples to suggest that highly intact landscapes are highly functional and diverse, whereas degraded landscapes have lost some functionality and species variety and abundance. Similar examples can be found in the published results of international rangeland studies (De Soyza *et al.* 2000; Osem *et al.* 2002), although for brevity these examples have not been reviewed here.

To progress our understanding of how biodiversity and landscape functional integrity are related, further studies are needed. For example, we need to understand better at what level a landscape is sufficiently intact to provide a variety of habitats suitable to maintain viable populations of species at scales appropriate to a given rangeland region (particularly with regard to rainfall variability in the arid zone). This scale issue is important because a landscape may appear to be intact or to have functional integrity at a fine-scale but, overall, it may be degrading when viewed at a large-scale. As studies proceed, we anticipate that significant relationships will be found between patch obstructions viewed at many scales, from log mounds on a hillslope to wetland sinks on a floodplain, where these patch obstructions capture and hold resources and provide habitat quality (food and shelter) for biodiversity.

We also need to understand better the persistence of habitat patches over time. Changes in patchiness could be tracked using time-traces of spatial-variance structures for rangelands, which can be derived from remotely sensed imagery (Pickup & Chewings 1986). For example, if a perennial grassland area with a relatively uniform cover of patches or tussocks (low variance) became degraded or less intact, evident by the development of patches of bare soil, this would be reflected in a higher spatial variance. We need to establish what biodiversity values relate to these spatial-variance measures.

To determine better the potential role of patch obstructions for conserving biodiversity, we suggest that questions such as the following need to be addressed:

1. What conditions of resource supply in time and space are required for different key taxa to occur in different places? For example, can a landscape on a given soil type, with its current geomorphic structure, provide adequate soil water supply for key plant taxa to survive the dry periods that are such a feature of Australia's rangelands?
2. When is resource redistribution needed in a landscape to allow key plant and animal taxa to persist and prosper where they would not if these resources were not redistributed into fertile patches or refugia?
3. What are the functional relationships between degree and frequency of disturbances such as clearing, grazing and fire and the amount of undisturbed landscape needed to support key taxa, particularly sufficiently unfragmented habitat for fauna?

These questions should be addressed within analytical frameworks that should include, but should not be limited to the following:

1. The trigger-transfer–reserve-pulse framework, which has spatial and temporal components that relate landscape patterns to processes at finer patch-hillslope scales (Ludwig *et al.* 1997); this framework has proven useful for identifying ecological indicators of landscape functionality applicable for monitoring rangelands (Tongway & Hindley 2000).
2. Biodiversity monitoring frameworks specifically designed for Australian rangelands (ACRIS 2001; Smyth *et al.* 2003); these frameworks should accommodate a range of inputs and include components that can be refined with time (Whitehead 2000).

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