

Results and discussion

Distribution (and scale of organization) of carbon was different in the four landscapes, with finer-scale features noted in meso-patches (Fig. 1). Anisotropy (asymmetry in distributions) was noted at the community scale. Maximum anisotropy (R_{\max} , direction with longest distribution range of high carbon) was across the slope, while minimum anisotropy (R_{\min} , direction with shortest distribution range of high carbon) was oriented with the slope. Meso-patch distributions (R_{patch}) lacked this pattern, except at the recovering site. At both scales, areas with high carbon levels became smaller and more widely distributed within progressively larger zones of low carbon as paddock condition declined (intact > degrading > degraded trajectory). High soil carbon zones were present on the recovering paddock, but were separated by large low carbon areas, resulting in a pronounced 'banding' effect.

Grazing pressure reduced herbaceous plant-derived carbon in these tropical soils, and caused major changes in distribution patterns within 4 years (Fig. 1). The small, localized high carbon zones that corresponded to areas with healthy perennial tussocks were less frequent as these grasses were replaced by less productive herbaceous species. Recovery mechanisms on long-term overgrazed areas differ from the degradation trajectory, and require longer time periods. The intact, degrading and recovering areas (at both scales) apparently operate by runon-runoff mechanisms that were negatively affected by heavy grazing pressure, resulting in eventual landscape dysfunction (Ludwig *et al.* 1997). The degrading site lost fine-scale structure, while the degraded area had few control

features left. This caused a negative synergistic effect, in which fewer resources were incorporated into reserve pools in the soil, resulting in reduced pulses of growth, and lowered inputs of organic matter which is the key to maintaining carbon levels.

Given the rapid loss of soil carbon at the meso-scale and community level, and slow recovery rate, grazing management within the woodlands of northern Australia should seek to prevent even minor landscape degradation (Ludwig *et al.* 1997). If large-scale degradation occurs, remedial treatments are unlikely to be economically viable, and ecological recovery will result only if managers adopt a long-term (e.g. decades) view.

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Banded vegetation and soil patterns in the Stockton Plateau, west Texas, USA

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Introduction

Banded vegetation patterns, consisting of regularly spaced strips of vegetation oriented parallel to contours on slopes with about 1% gradient, were first noted in 1947 on high resolution aerial photographs of the Somaliland Protectorate (Macfayden 1950). Similar intermittent bands of vegetation occur on more than 590 000 ha in Trans-Pecos, Texas. Banded patterns appear to function as mechanisms for resource partitioning and nutrient cycling, and may result in a more stable landscape (Ludwig & Tongway 1995). Because resource management practices potentially affect these processes, a knowledge of pattern origin and the influence of boundaries on ecological processes is necessary to develop proper management principles (Wiens *et al.* 1985).

Water is the primary limiting factor for plant growth on most rangelands. At the local level, plant water availability is determined by infiltration capacity and water storage capacity of soils. Water intake capacity is a function of soil structure, bulk density, and particle size distribution, whereas water storage capacity is controlled by texture, rock fragment content and depth. Few studies of banded vegetation patterns have examined soil properties below the surface horizon. The objectives of this study were to (i) quantify vegetative cover and relief, (ii) ascertain whether boundaries exist, (iii) describe the morphology of soils, and (iv) quantify selected soil physical and chemical properties, with the ultimate aim of identifying relationships between soil properties and banded vegetation.

Materials and methods

This study was conducted in the Stockton Plateau, 64 km south-east of Fort Stockton, Texas (30°36'N 102°35'W). The climate is semi-arid (mean annual precipitation 35.2 cm, potential evapotranspiration 95.6 cm). Mean air temperature is 8.3°C in winter and 26.7°C in summer. The site (at altitude 980 m) is on a gently sloping slightly concave pediment underlain by Cretaceous limestone. Soils were mapped as an association of deep (>150 cm) Reagan and Hodgins silty clay loams, with inclusions of Dalby, Iraan, and Upton soils (Rives 1980). The area has been grazed by cattle and sheep since the late 1800s and has no history of mechanical or chemical vegetation manipulation.

Banded vegetation was sampled along a 750 m transect oriented normal to slope contours and vegetation bands. Foliar cover by species (nomenclature follows Hatch *et al.* 1990) was estimated in 0.5 m x 1.0 m quadrats ($n = 255$) located at 3 m intervals. Boundary locations between bands were visually estimated by two observers familiar with vegetation patterns in the area.

To objectively identify discontinuities, transect data were subjected to a boundary analysis procedure (window width = 6; Ludwig & Cornelius 1987). Differences in vegetative cover between community types delimited by boundary analysis were analysed with one-way ANOVA followed by Tukey's mean comparison test ($P \leq 0.05$). Cluster analysis was performed using MVSP (Kovach 1995) to further elucidate community types.

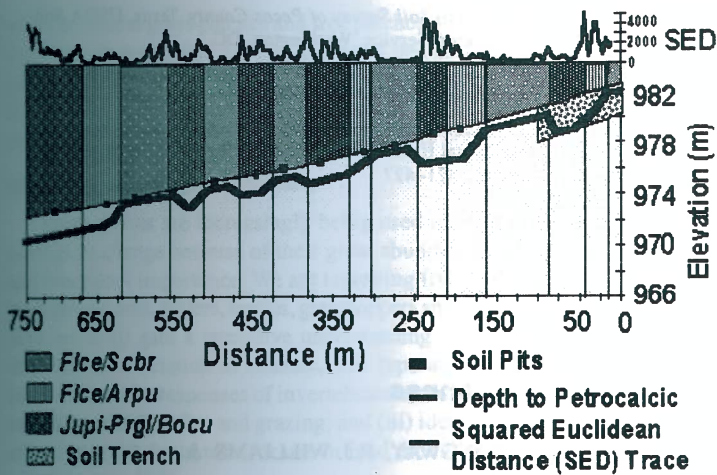


Fig. 1. Land surface profile along vegetation transect illustrating SED trace, community types, location of soil trench and pits, and depth to petrocalcic horizon

A trench, 115 m long and 200 cm deep, was excavated with a backhoe, parallel to the upper portion of the vegetation transect. Soil morphology at every third metre was described (Soil Survey Staff 1993), cementation of calcic horizons was noted, and samples were taken from horizons of 34 pedons. Along the transect, 12 pits were excavated to 60 cm with hand tools to confirm depth to a petrocalcic horizon. Elevation along the 750 m transect was surveyed at 25 m intervals with an electronic theodolite; elevation beside the trench was determined at 3 m intervals with a transit and stadia rod.

Laboratory characterization was performed for three complete pedons. Particle size distribution was determined by a modified hydrometer method, organic carbon by a modified Walkley-Black method, and calcium carbonate equivalent by acid neutralization (Page 1982). Available water for each pedon was computed on a volumetric basis using the Rawls algorithm (Kern 1995).

Results

Vegetation bands occurred as three physiognomically distinct community types: *Flourensia cernua*/Scleropogon brevifolius shrubland (Ffice/Scbr); *Flourensia cernua*/Aristida purpurea grassland (Ffice/Arpu); and *Juniperus pinchotii*-Prosopis glandulosa/Bouteloua curtipendula woodland (Jupi-Prgl/Bocu). Results from cluster analysis and mean separation tests among key species substantiated the three community types. Bands recurred sequentially down slope, and location of community type discontinuities determined by boundary analysis (indicated by peaks in the squared Euclidean distance (SED) trace) largely agreed with subjective placement (Fig. 1). Foliar cover in the shrubland comprised mainly *Flourensia cernua* (7.2%) and *Scleropogon brevifolius* (11.2%). The grassland was dominated by *Flourensia cernua* (13.7%), *Aristida purpurea* (12.6%), *Buchloe dactyloides* (8.6) and *Scleropogon brevifolius* (5.5%). *Juniperus pinchotii* (8.9%), *Prosopis glandulosa* (6.0%), *Flourensia cernua* (11.1%), *Bouteloua curtipendula* (7.7%), and *Buchloe dactyloides* (7.4%) dominated the woodland. Total woody/herbaceous cover (%) was 10/14 in Ffice/Scbr, 22/34 in Ffice/Arpu, and 30/20 in Jupi-Prgl/Bocu.

Each of the three distinct soils in the trench corresponded well with a specific community type. The shallow Upton soil characterized the Ffice/Scbr shrubland along the trench as well as along the vegetation transect (Fig. 1). The petrocalcic horizon limited water storage and restricted root growth. The Reagan soil supported Ffice/Arpu grassland. Depth to a non-cemented calcic horizon ranged from 60 to 150 cm. The deep Hodgins soil contained neither a calcic horizon nor a root

restrictive layer within 200 cm, so plants could more completely use soil water resources. This soil was associated with the Jupi-Prgl/Bocu woodland.

To a depth of 50 cm the three soils had similar physical and chemical properties. Differences in the content and cementation of CaCO₃ in horizons below 50 cm partially controlled plant available water, which was 7.2 cm, 18.7 cm, and 27.0 cm, in the Upton, Reagan, and Hodgins soils, respectively (Fig. 2).

Discussion

In arid ecosystems where the topography and soils vary markedly in space (Crawford & Gosz 1982), edaphic control of landscape patterns can be especially strong (Wiens *et al.* 1985). Depth to a petrocalcic horizon in this system seems to control the type of vegetation present on a particular site, primarily because water storage capacity is a function of soil depth. Woody plants, in general, have maximum rooting depths of 5 m whereas grass roots extend to approximately 2.5 m (Canadell *et al.* 1996). In semi-arid environments, shallow soils support less productive vegetation, in this case a sparse shrubland, than deep soils which here support more productive grassland and woodland community types.

Subsurface features at least partially regulate the vegetation pattern at this location, though runoff/runon (source/sink) relationships may also play an important role. No shrub management is recommended on the Upton soil (Ffice/Scbr ct) because of its limited response potential. 'Narrowcast' shrub management, consisting of selective removal of woody plants from the deep Reagan and Hodgins soils (Ffice/Arpu and Jupi-Prgl/Bocu community types), may be feasible to increase forage production.

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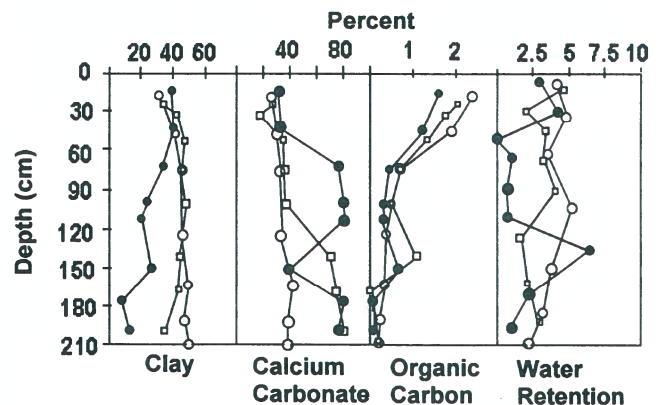


Fig. 2. Depth functions of clay, calcium carbonate, organic carbon, and water retention for three soil series in the Stockton Plateau, Texas (● = Upton, □ = Reagan, ○ = Hodgins)

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Indicators of ecosystem change in north Australian savannas

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Introduction

Savannas are characterized by the co-dominance of trees and grasses. They dominate tropical and sub-tropical regions of the world where rainfall is highly seasonal. The productivity and biodiversity of savannas is coming under increasing pressure because they are home to nearly one fifth of the world's population. Pressures to develop land in a multitude of ways are increasing, but so too are pressures for land to be used sustainably (Taylor & Braithwaite 1996). In marked contrast to other savanna regions around the world, north Australia has an extremely low human population density and there has been little land clearing, wood harvesting or cropping. Unlike other parts of Australia, there have been no extinctions of vertebrate fauna since European settlement (Woinarski & Braithwaite 1990). Nevertheless, many species of mammals and ground-feeding granivorous birds have suffered recent range reductions (Braithwaite & Griffiths 1994; D.C. Franklin pers. comm.). This suggests that the grass stratum of these savannas is changing in response to commercial grazing and altered fire regimes.

In order to document changes in the north Australian savanna, we aim to develop robust indicators of changes in land condition and biological diversity in Australia's tropical savannas. These indicators must be based on a sound understanding of ecosystem and landscape function. They need to be sensitive to changes induced by management actions and they must take account of the range of soils and rainfall regimes across the savanna zone. In this paper, we describe our progress in developing those indicators.

Indicators of landscape function

Many semi-arid and arid systems are characterized by patterns of fertile and infertile patches. An understanding of this heterogeneity of resources should be an important step towards an understanding of savanna ecosystems and landscapes. The fertile patches are important components of many ecosystems because they capture and retain water and nutrient resources (Tongway & Ludwig 1997). We hypothesized that the patterns of heterogeneity would vary systematically across soil types and with variation in water availability. Generally, arid and semi-arid areas worldwide tend to have larger patches than more mesic areas. Our studies along the rainfall gradient in north-western Australia confirm this. We found that landscape patches on sand and loam soils decline in cover with increasing rainfall as illustrated by the percentage patch cover on sand sites (Fig. 1a). This decline is negatively related to tree canopy cover along the rainfall gradient (Fig. 1b) because as tree canopy cover increases with rainfall (Williams *et al.* 1996; Ludwig *et al.* 1999), ground-layer patch cover declines. We find that soil

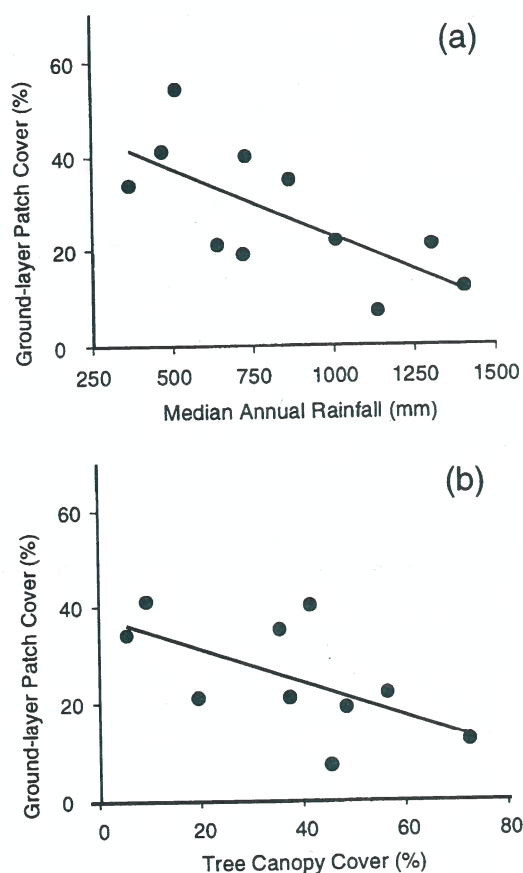


Fig. 1. The decline in total ground-layer patch cover with increasing (a) rainfall, and (b) tree canopy cover, on sand sites, north Australia

Table 1. Mean concentrations of soil organic nitrogen (Kjeldahl N, 0–10 cm depth) within perennial grass and tree patches in comparison to inter-patch areas for loam soils located at five savanna sites in north Australia

Site	Total organic nitrogen (%)		
	Grass patch	Tree patch	Inter-patch
Mount Sanford	0.051	0.142	0.042
Kidman Springs	0.144	0.217	0.116
Willeroo	0.080	0.159	0.056
Douglas Daly	0.063	0.100	0.059
Annaburroo	0.088	0.120	0.073