



## A QUANTITATIVE STATE AND TRANSITION MODEL FOR THE MITCHELL GRASSLANDS OF CENTRAL WESTERN QUEENSLAND

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### Abstract

Concerns of reduced productivity and land degradation in the Mitchell grasslands of central western Queensland were addressed through a range monitoring program to interpret condition and trend. Botanical and edaphic parameters were recorded along piosphere and grazing gradients, and across fenceline impact areas, to maximise changes resulting from grazing. The Degradation Gradient Method was used in conjunction with State and Transition Models to develop models of rangeland dynamics and condition. States were found to be ordered along a degradation gradient, indicator species developed according to rainfall trends and transitions determined from field data and available literature. *Astrebla* spp. abundance declined with declining range condition and increasing grazing pressure, while annual grasses and forbs increased in dominance under poor range condition. Soil erosion increased and litter decreased with decreasing range condition. An approach to quantitatively define states within a variable rainfall environment based upon a time-series ordination analysis is described.

The derived model could provide the interpretive framework necessary to integrate on-ground monitoring, remote sensing and geographic information systems to trace states and transitions at the paddock scale. However, further work is needed to determine the full catalogue of states and transitions and to refine the model for application at the paddock scale.

**Key words:** *Astrebla*; State and Transition Models; Degradation Gradient Method; range condition; Mitchell grasslands; grazing impacts, central western Queensland

### Introduction

The Mitchell grasslands are the most extensive and productive native pastures of semi-arid western Queensland (Lee *et al.* 1980). They cover 33 million ha within Queensland, supporting 45% of the State's sheep and 10% of the cattle. The Northern Territory, Western Australia, New South Wales and South Australia share a further 11.8 million ha of Mitchell grasslands (Orr 1975).

The grasslands are dominated by the long-lived perennial *Astrebla* spp. (Mitchell grasses). The basal cover of these tussock grasslands is low (1 to 6%), and rainfall is highly variable, leading to fluctuations in both pasture yield and composition (Orr 1975, 1981). A change from summer to winter rainfall dominance, moving from the north to the south of Queensland also affects pasture yield and composition, particularly of inter-tussock annual and ephemeral species (Orr and Holmes 1984). This creates spatial and temporal differences when assessing rangeland condition within the Mitchell grasslands and led Everist and Webb (1975) to conclude that "the extrapolation from [vegetation] observations made at any one time can be misleading and inaccurate".

State and Transition Models (Westoby *et al.* 1989) have recently supplanted Clementsian successional theory (e.g. Clements 1916, 1936, Dyksterhuis 1949) in explaining vegetation based changes in rangeland condition. Reasons for this paradigm shift are given in recent publications (e.g. Whalley 1994, Brown 1994) and generally relate to the inability of succession to explain vegetational instability in the absence of disturbance.

Clementsian successional theory is a framework for interpreting change in vegetation. It is based on the idea of a singular trajectory through a series of states, separated by a threshold. This model is used to help agents understand and manage the process (Bosch *et al.* 1999).

Successful implementation of State and Transition Models requires managers to acknowledge the value of local knowledge through a continuum, even in the absence of a full understanding.

This paper describes the application of State and Transition Models to central western Queensland. The models were developed in 1989 in response to a perceived declining range condition (Tothill and Gillies 1991).

### Materials and Methods

#### Data collection

##### Vegetation survey

Fifty-seven sites of different conditional states (including camp transects and Kellner 1991) representative of the central Mitchell grasslands (presented) were located in the district) and south of the district) separated to avoid rainfall gradients (F

The sites were initially surveyed in May 1993 and May 1994. The nearest plant method was used (instead of the nearest plant method) site. Similar methods were used (Hardy and Walker 1991).

##### Site descriptions

All sites were initially classified into Land Zone (Turner 1991) and general edaphic parameters were recorded (disturbance (e.g. erosion) to methods detailed in Bosch *et al.* (1999) distribution (data not available).

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Clementsian successional theory, however, formed the foundation of many modern techniques for interpreting changes in rangeland condition. The Degradation Gradient Method (DGM, Bosch and Gauch 1991) is Clementsian based, with thresholds and domains of attraction ordered along a singular gradient. Domains can be equated with major states in State and Transition Models (Bosch and Kellner 1991) and irreversible changes occur when domains of attraction are separated by a threshold. Models based on the DGM have been used in the New Zealand high country to help agency staff, graziers and funding bodies interpret vegetation monitoring results and serve as the basis for natural resource decision making within an adaptive management process (Bosch *et al.* 1996).

Successful implementation of sustainable best management practices ultimately rests with land managers. Watson *et al.* (1996) argue that the "mental models held by managers must acknowledge the value of continuous change. This provides the best opportunity for acquiring knowledge through experience". In this, they acknowledge the benefits of perceiving changes as a continuum, even if State and Transition event driven models provide a deeper ecological understanding.

This paper describes an approach by which both Clementsian and State and Transition theories were applied concurrently to develop models of the dynamics of the Mitchell grasslands in central western Queensland. Data were obtained from a pasture monitoring program established in 1989 in response to concerns by the pastoral industry and the scientific community about perceived declining productivity and rangeland degradation (e.g. Roberts and Crouch *ca.* 1989, Tothill and Gillies 1992).

## Materials and Methods

### Data collection

#### Vegetation surveys

Fifty-seven sites of 30 by 30 m square were permanently marked to represent different conditional states (e.g. within existing grazing trials, fence line effects, piosphere and stock camp transects and sheepwalks) within a relatively homogeneous grazing area (RHGA, Bosch and Kellner 1991) of the central Mitchell grasslands (Fig. 1a). The RHGA study area was representative of the slightly concave flats dominant on the Undulating downs Land Zone of the central Mitchell grasslands (Fig. 1b, Turner *et al.* 1993). Further RHGA study areas (data not presented) were located within the northern Mitchell grasslands (Julia Creek - Richmond district) and southern Mitchell grasslands (Blackall district). These areas were deliberately separated to avoid broad differences in vegetation patterns along both north-south and east-west rainfall gradients (Fensham *et al.* 2000) unduly influencing potential grazing impacts.

The sites were initially surveyed in August 1989 and re-surveyed in January 1990, May 1991, May 1993 and May 1994. Site botanical composition was assessed using a modification of the nearest plant method (Evans and Love 1957), with the nearest plant within a 200 mm radius (instead of the nearest plant irrespective of distance) recorded at 200 points within each survey site. Similar methods capture at least 95% of the total mix of plant species in African rangelands (Hardy and Walker 1991, Stalmans and Mentis 1993).

#### Site descriptions

All sites were initially described (Table 1) based on Land Systems within the Undulating downs Land Zone (Turner *et al.* 1993), greater soil group (Northcote 1979, Northcote *et al.* 1975), general edaphic properties (e.g. soil depth, topography, and slope position) and evidence of disturbance (e.g. erosion activity). Bulked surface samples (0 - 10 cm) were analysed according to methods detailed by Bruce and Rayment (1982) to provide soil chemistry and particle size distribution (data not presented).

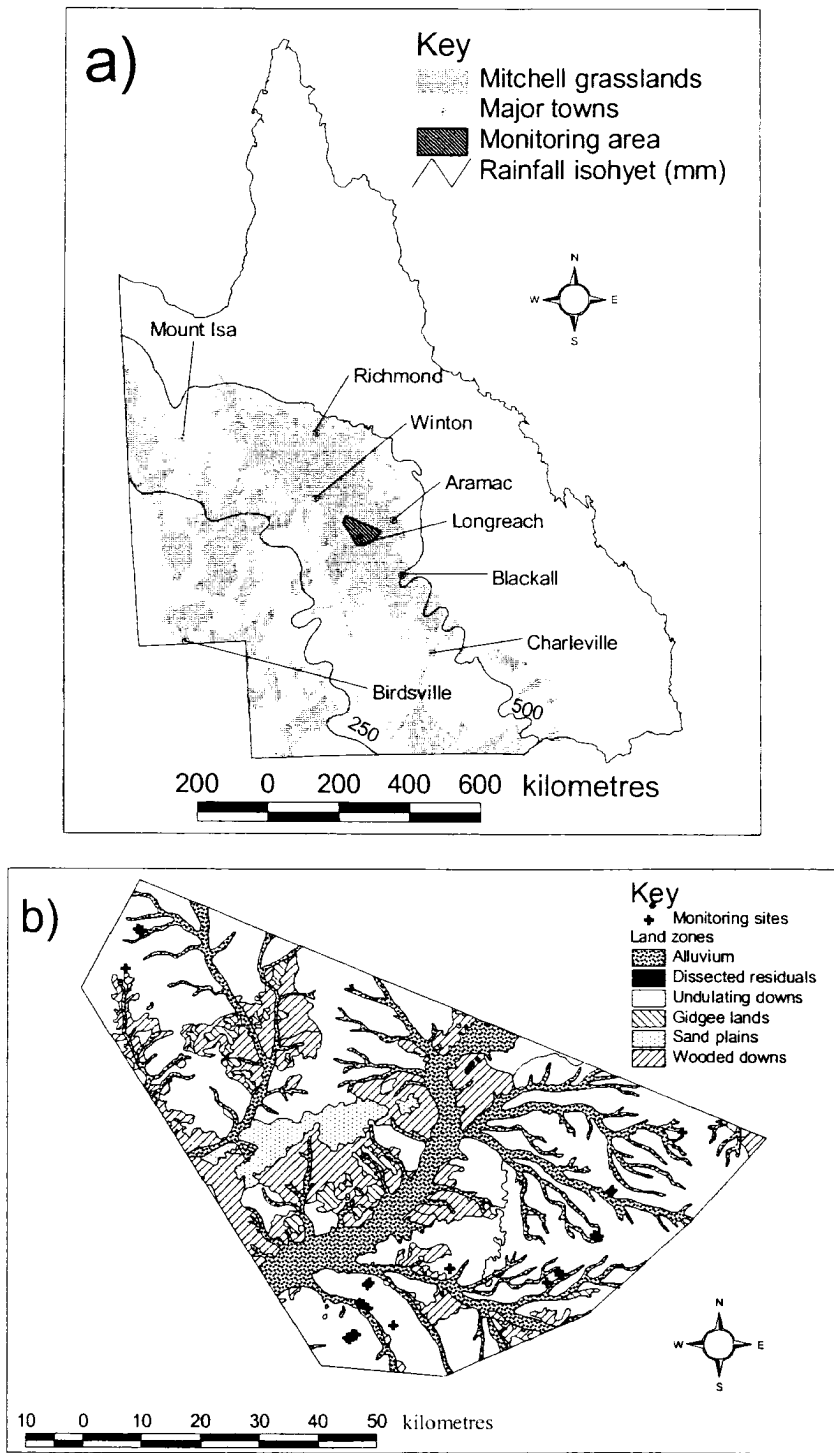


Fig. 1. The location of: a) the study area in relation to Longreach and the Mitchell grasslands of Queensland; and b) monitoring sites in relation to Land Zones (Turner *et al.* 1993) of the study area.

Above ground biomass was estimated using photostandards (Phelps *et al.* 1993). The percentage of above ground biomass was estimated at each site using a point intercept method. Data were interpolated from the Natural Resource Survey (Department of Resources and Mines) from Birdsville to Longreach. This data was used for assessing the relationship between rainfall and biomass.

*Data analysis*

*Identifying vegetation groups*

Firstly, each record was assigned to a seasonal rainfall pattern based on site habitat differences. Species that occurred in each pattern were used to minimise noise in the ordination for Plant Dynamics, and the ordination of data (through the use of ordination techniques (Gauch 1985)) was centred ordination. Clustering with DCA identified vegetation groups defined as vegetation types. PCA (a possible detrended correspondence analysis) and Kellner 1991, 1992 were used to identify vegetation groups.

Secondly, individual sites were plotted in ordination space from one state to another. Changes in vegetation states, and the movement of sites over time, were taken as evidence of vegetation transitions between stable vegetation states. The ordination was time independent, together in ordination space. *Sida* spp. over the study area, whilst another group of species, *Dichanthium sericeum*, was the results and discussed in the next section.

*Defining a degradation gradient*

Edaphic factors and grazing levels within grazed areas were used in ordination diagrams to position the sites along a degradation gradient within each date site. The ordination was quantified vegetation types.

<sup>1</sup> See Table 2 for species list.

Above ground biomass (kg/ha) and grazing pressure (utilisation level, %) were estimated from photostandards (Phelps and Bates 1994, Orr 1978) at each site on each survey. Ground cover (%) was estimated in May 1991 from photographic slides of three random 1 m<sup>2</sup> quadrats within each site using a point intercept method on a projection screen (Day and Philp 1997). Rainfall data were interpolated from site positions (longitude and latitude) by the Climate Impacts and Natural Resource Systems Group (Natural Resource Sciences, Department of Natural Resources and Mines) from Bureau of Meteorology data (McKeon *et al.* 1998). This suite of habitat data was used for assessing the major factors influencing variation in vegetation composition.

### Data analysis

#### Identifying vegetation states

Firstly, each recording date was ordinated independently in a time-series approach to avoid seasonal rainfall patterns unduly influencing the proportional plant abundance data. Outliers due to site habitat differences (e.g. extremes of pH, differences in Land System classifications) and species that occurred at less than 15% of the survey sites were removed prior to ordination to minimise noise in the data set (Gauch 1982). The software packages ISPD (an Integrated System for Plant Dynamics, Bosch *et al.* 1992) and PATN (Belbin 1987) were used to explore the best fit of data (through the analytical component of ISPD and by eye) within a range of ordination techniques (Gauch 1982). For each recording, an adapted PCA (Principal Components Analysis) centred ordination (Bosch and Gauch 1991) proved to be the most suitable, following initial clustering with DCA (Detrended Correspondence Analysis, Hill and Gauch 1980). Different vegetation groups were identified by eye in ISPD (Bosch *et al.* 1992) and these groups then defined as vegetation states (e.g. State A (1989) in Fig. 2) relative to the first ordination axis of PCA (a possible degradation gradient), with the second axis defined as a residual score (Bosch and Kellner 1991, Bosch and Gauch 1991).

Secondly, individual sites within each state were identified and their movement in ordination space from one state to another traced over time. This process provided evidence of generalised vegetation states, directions of change (or transitions) and the possible reversibility of the changes. The movement of groups of sites between similar vegetation states across sampling dates was taken as evidence of the presence of a single stable vegetation state (the solid arrows of Fig. 2). The movement of individual sites against a general trend was taken as evidence of transitions between vegetation states (the dashed arrows of Fig. 2). The combined evidence of stable vegetation states and the existence of transitions was utilised in defining a generalised, time independent, State and Transition Model (STM). For example, the same sites grouped together in ordination space on the basis of high proportions of *Malvastrum americanum*<sup>1</sup> and *Sida* spp. over the "average summer, wet winter" between August 1989 and January 1990, whilst another group of sites grouped on the basis of high proportions of *Astrebla* spp. and *Dichanthium sericeum* (Fig. 2). Details of site movements and vegetation states are provided in the results and discussion section.

#### Defining a degradation gradient and identifying indicator species

Edaphic factors and known management histories (e.g. protected sites, sites of known utilisation levels within grazing trials, sites close to watering points and stock camps) were plotted on the ordination diagrams at each date. This allowed the main ecological factor(s) responsible for the positioning of the states along the first axis to be defined, and to clarify or reject its status as a degradation gradient within each sampling date. The acceptance of the first ordination axis within each date specific data set as a degradation gradient was a prerequisite for condensing the quantified vegetation states into generalised vegetation states.

<sup>1</sup> See Table 2 for species nomenclature and descriptive information

Table 1. Site parameters measured during the study period.

Parameter	Recordings/Measurements conducted	Recording Dates
Vegetation composition	Plant species abundance (%)	all
Management history	Above ground biomass (kg/ha), grazing pressure (utilisation level, %) and evidence of disturbance	all
Daily rainfall	Interpolated daily rainfall (mm)	all
Photographic records	Landscape view photograph on slide film	all
Site location	Longitude and latitude (Global Positioning System), land system (e.g. F3 undulating downs), and site location in relation to landform elements (slope category e.g. gentle incline, landscape position e.g. mid-slope, shape e.g. convex, inclination e.g. waning, geomorphology agent e.g. sheet erosion, element e.g. hillslope, pattern e.g. undulating plain, relief (m), modal slope (%), slope (%), aspect (degrees), class e.g. gentle undulating plain)	August 1989
Site description	Physical parameters within the site including microrrelief e.g. crab hole gilgai, vertical and horizontal intervals (m), erosion classes (state e.g. active, type e.g. sheet, degree of e.g. slight and evidence for e.g. accumulated fine sand), surface coarse fragments (aggregation e.g. fine sand accumulation, size in mm, shape e.g. rounded and lithology e.g. ironstone), rock outcrops (abundance, %, and lithology e.g. sandstone) and geology e.g. sandstone	August 1989
Soil classification	Greater soil group (e.g. brown cracking clay), soil depth (cm), colour e.g. DY brown, texture (e.g. medium clay, MC), structure (e.g. W4AB), consistency (e.g. moderate to weak) and coarse fragments (e.g. ironstone) through the profile (up to 1 m depth)	August 1989
Soil surface condition	Observable disturbance mechanisms, including type of grazing animal (cattle or sheep), grazing impact (disturbance level e.g. recently grazed), dominant surface condition (e.g. crusting) and rating (e.g. moderate), litter level rating (nil, some, moderate, high)	August 1989
Soil chemistry	pH and electrical conductivity (mS/cm) (1:5 soil:water), nitrogen (total, %, and nitrate-N, mg/kg), phosphorus (total, %, and bicarbonate extractable, mg/kg), potassium (total, %, and acid extractable, mg/kg), organic carbon (Walkley and Black, %), cation exchange capacity (milliequivalents/100g), chloride (mg/kg), calcium (%), magnesium (%), sodium (%), sulfur (%), DTPA extractable copper, zinc, manganese and iron (mg/kg), air dry moisture content (ADMC, % dry weight)	August 1989
Soil particle size distribution	Clay (%), silt, (%), fine sand (%), and coarse sand (%)	August 1989
Litter class	Ground cover (%)	May 1991

Survey date

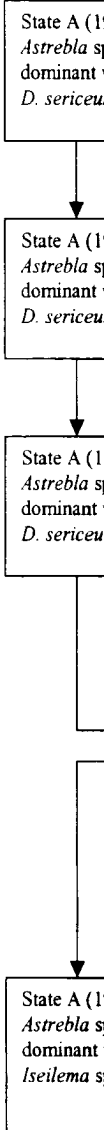
August 1989

January 1990

April 1991

May 1993

May 1994

Fig. 2. Movement of State A (1) *Astrebla* sp. dominant *D. sericea* (boxes represent well-developed sites, and empty boxes represent poorly developed sites; arrows represent general movement of sites; the proportion of sites in each state is indicated by the size of the boxes).Once the first axis of variation is plotted against PC1 (Bosch *et al.* 1999).

Survey date

Vegetation states and changes

Rainfall trends

mg/kg, phosphorus (total, %, and bicarbonate extractable, mg/kg), potassium (total, %, and acid extractable, mg/kg), organic carbon (Walkley and Black, %), cation exchange capacity (milliequivalents/100g), chloride (mg/kg), calcium (%), magnesium (%), sodium (%), sulfur (%), DTPA extractable copper, zinc, manganese and iron (mg/kg), air dry moisture content (ADMC, % dry weight)  
 Clay (%), silt, (%), fine sand (%), and coarse sand (%)  
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 Litter class

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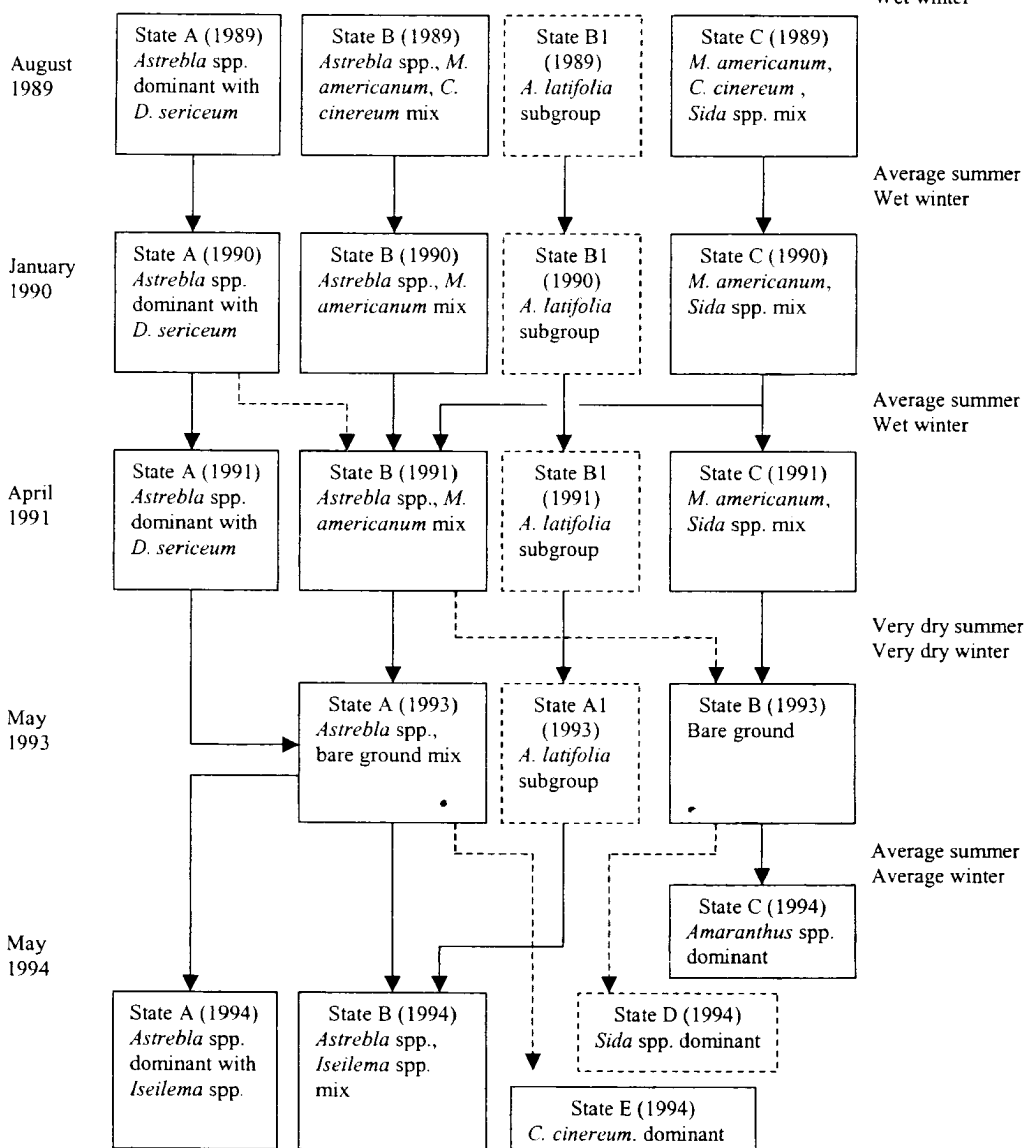


Fig. 2. Movement of sites between vegetation states formed from one date to another. Solid boxes represent well defined states (the grouping of a large number of sites), dashed boxes represent poorly defined states (the grouping of a small number of sites). Solid lines indicate a general movements of sites, dashed lines indicate the movement of individual (or a small proportion of) sites.

Once the first axis was confirmed as a degradation gradient, the abundances of species were plotted against PCA axis one, and Gaussian fit regression analyses performed using ISPD (Bosch *et al.* 1992, Bosch and Kellner 1991). Indicator species were defined as those with

significant  $R^2$  values ( $P < 0.05$ ) in relation to the first ordination axis, and with relatively high abundances in the Mitchell grasslands.

Data from sample dates with common indicator species displaying similar trends under similar rainfall conditions (e.g. the "average summer, wet winter" preceding August 1989, January 1990 and April 1991, Fig. 2) were grouped and re-analysed using PCA. As long as the same species and trends persisted, the combined model was used as a basis for more generalised indicator species curves (e.g. August 1989, January 1990 and April 1991 data were combined to become "Following major drought"). Where the same species and trends did not persist, the ability to combine data sets was rejected and individual data sets formed the basis of the indicator species curves. Consequently May 1993 and May 1994 became "During seasonal drought" and "Following seasonal drought" respectively. Details of combined models and indicator species curves are provided in "Determining Indicator species" within the results and discussion section.

The relative strength of indicator species as decreaseers or increaseers along the degradation gradient (axis one) was used to define the position of states (including sub-groups) within the generalised STM. Hence the high abundance of bare ground (a strong increaseer species) in State VII, coupled with the absence of other species, suggested it to be the most degraded state. High abundances of *Cullen cinereum* within State III suggested it to be less degraded than State V, despite the strength of *M. americanum* as an increaseer species. This evidence was reinforced through a tendency for degraded sites to be more common within States VII, VI and V.

#### Data availability

Data sets are available from the first author upon request, or can be found appended to Phelps (1999).

## Results and Discussion

### Identification of vegetation states

The main vegetation states identified from the ordination diagrams of each date are presented in Fig. 2. States were numbered for the individual ordinations at each field recording time. State A in August 1989 should thus not be considered as the equivalent to State A in May 1993, for example. The vegetation states are presented in the same order in which they appeared along the first ordination axis, although the relative length of each first axis is not provided. Vertical differences in May 1994 are for ease of presentation and do not reflect the second (residual) axis.

The general movement of sites through subsequent time specific ordinations is indicated by solid arrows, with August 1989 used as the baseline ordination. This general movement represents the creation of new ordinated vegetation groups at different times which may be similar to, or dissimilar from, the ordinated vegetation group in the preceding time and were assumed to represent time specific states. For example, the single arrow from State A (1989) to State A (1990) indicates that all the sites ordinated in this state in the August 1989 data were also ordinated in this state in the January 1990 data, reflecting stability over this time period. Stability of this kind was later used as evidence in determining generalised vegetation states.

The movement of a small proportion of sites against the general trend through subsequent ordinations is indicated by dashed arrows. For example, some sites moved from State C (1990) to State C (1991), whilst others were now ordinated in the State B (1991) group of sites. Instability of this kind was later used as evidence in determining transitions.

The temporal movement of sites to form new states is provided in the following descriptions:

### Changes in State

This grassland, dominated by *A. pectinata* but rare by 1993 most of the drought. After more was replaced by *Is* *Iseilema* spp. A shrubby grassland with *As* was against the general trend (presented), it could not. There was some evidence of *Astrebla* spp. may be a relatively lower percentage into a separate category.

### Changes in State

This grassland, dominated by *C. cinereum* between 1989 and 1993 induced this vegetation response to change following wet seasons. Although *M. americanum* remained following dry conditions to overgrazing during most of the sites changed to a *C. cinereum*.

### Changes in State

This grassland, with *C. cinereum* between 1989, and remained in this group changed to a different group following improved conditions.

### Changes in State

This herbfield, dominated by *S. trichopoda* and *S. trichopoda*. This shift in botanical composition (grassland with *As* in 1991) following a May 1993 following a mean rainfall result in loss suggests a more favourable conditions than either (primarily *A. mitchellii*) had remained in a different group May 1994.

The analysis has implications for botanical composition and other studies (e.g. rainfall influence,

*Changes in State A (1989, Astrebla spp. dominant with D. sericeum)*

This grassland, dominated by *Astrebla* spp. (primarily *A. lappacea* and *A. elymoides*, with some *A. pectinata* but rarely *A. squarrosa*), stayed the same during average to good rainfall years but by 1993 most of the *D. sericeum* (a palatable perennial grass, Table 2) had been lost following drought. After more favourable rainfall conditions over the 1993/94 summer period, bare ground was replaced by *Iseilema* spp. to form grassland dominated by *Astrebla* spp. with occurrences of *Iseilema* spp. A small number of sites in the grassland dominated by *Astrebla* spp. changed to grassland with *Astrebla* spp. mostly dominant between January 1990 and April 1991. Since this was against the general trend and rainfall conditions did not vary substantially (data not presented), it could be assumed that this resulted from increased grazing pressure at these sites. There was some evidence (data not presented) that the grouping of *A. squarrosa* with all other *Astrebla* spp. may cloud the correct interpretation of vegetation dynamics, especially given its relatively lower palatability (Table 2) and preference for run-on areas (Orr 1975). Its separation into a separate category would be recommended for future monitoring programs.

*Changes in State B (1989, Astrebla spp., M. americanum, C cinereum mix)*

This grassland, mostly dominated by *Astrebla* spp., retained *M. americanum* but lost *C. cinereum* between August 1989 and January 1990. A change in rainfall patterns may have induced this vegetation shift. Bushell *et al.* (1993) found the density of both species declined in response to changed rainfall patterns, whilst *C. cinereum* increases are often associated with cool wet seasons. Alternatively, the change may reflect greater *M. americanum* persistence. *M. americanum* remained abundant until May 1993 when it was replaced with bare ground following dry conditions, with the exception of two sites which lost all plant cover (probably due to overgrazing during dry conditions). More favourable rainfall over the 1993/94 summer caused most of the sites to change into a mixed *Astrebla* spp. and *Iseilema* spp. state, whilst some changed to a *C. cinereum* dominant state.

*Changes in State B1 (1989, A. latifolia sub-group)*

This grassland, with a predominance of *Aristida latifolia*, formed a sub-group within State B in 1989, and remained the same until May 1993 when bare ground started to increase. This sub-group changed to an *Astrebla* spp. and *Iseilema* spp. mix by May 1994 (State B 1994). This followed improved rainfall conditions.

*Changes in State C (1989, M. americanum, C. cinereum, Sida spp. mix)*

This herbfield, dominated by *M. americanum*, *C. cinereum* and *Sida* spp. (primarily *S. fibulifera* and *S. trichopoda*), lost the *C. cinereum* component between August 1989 and January 1990. This shift in botanical composition coincided with the loss of *C. cinereum* from State B (grassland with *Astrebla* spp. mostly dominant). A small proportion of sites moved to State B (1991) following a reduction in *M. americanum* and *Sida* spp., but were generally returned in May 1993 following low summer and winter rainfall. This low rainfall (approximately 50% of mean rainfall) resulted in the complete loss of *M. americanum* and *Sida* spp. from all sites. This loss suggests a relatively unstable vegetation state which is more susceptible to drought conditions than either of the grassland states. The herbfield was dominated by *Amaranthus* spp. (primarily *A. mitchellii*) in May 1994 following improved rainfall conditions. The sites which had remained in a grassland state during 1991 and 1993 became dominated by *C. cinereum* in May 1994.

The analysis has indicated that rainfall was the dominant driving force for the major changes in botanical composition over time (represented by solid arrows in Fig. 2), a finding supported by other studies (e.g. Orr 1981, Roe and Allen 1993, Fensham *et al.* 2000). Within this dominant rainfall influence, other work has indicated that grazing can influence both short- and long-term

Table 2. Life form, longevity, palatability (Milson 1996, 2000) and nomenclature of species referred to in the text. Estimated longevity (in years) and palatability are provided as a guide for plant behaviour within the central Mitchell grasslands.

Species	Life form	Longevity	Palatability*
<i>Abutilon malvifolium</i> (Benth.) J.M.Black	Erect forb to 50 cm tall	Perennial (approx. 2-5 years)	L
<i>Amaranthus</i> spp. L.	Erect forbs to 50 cm tall	Annual	L
<i>Amaranthus mitchellii</i> Benth.	Erect forb to 30 cm tall	Annual	L
<i>Aristida latifolia</i> Domin.	Erect tussock grass to 1.3 m tall	Perennial (approx. 5-8 years)	L
<i>Astrelba</i> spp. F.Muell. ex Benth	Erect tussock grasses to 1.5 m tall	Perennial (approx. 20-30 years)	H
<i>Astrelba elymoides</i> F.Muell ex Bailey	Erect tussock grass to 60 cm tall	Perennial	H
<i>Astrelba lappacea</i> (Lindl.) Domin.	Erect tussock grass to 60 cm tall	Perennial	H
<i>Astrelba pectinata</i> (Lindl.) F. Muell. ex Benth	Erect tussock grass to 1 m tall	Perennial	H
<i>Astrelba squarrosa</i> C.E. Hubbard	Erect tussock grass to 1.5 m tall	Perennial	M to H
<i>Boerhavia diffusa</i> L. (under revision, <i>B. diffusa</i> is no longer valid in Australia)	Prostrate (generally) to erect (occasionally) forbs	Perennial (approx. 2-3 years)	L to M
<i>Cullen cinereum</i> (Lindl.) J.W. Grimes	Erect forb to 60 cm tall	Annual (to facultative perennial)	L
<i>Daucus glochidiatus</i> (Labill.) Fisch., C.A.Mey. & Ave-Lall.	Erect forb to 20 cm tall	Annual	H
<i>Desmodium campylocaulon</i> F.Muell. ex Benth.	Prostrate (trailing) legume	Perennial (approx. 2-3 years)	H
<i>Dichanthium sericeum</i> (R.Br.) A.Camus	Erect tussock grass to 60 cm tall	Perennial (approx. 5-8 years)	H
<i>Digitaria</i> spp. (F.Muell.) Hughes	Erect tussock grasses to 1 m tall	Perennial (possibly 5-10 years))	H
<i>Digitaria coenocola</i> (F.Muell.) Hughes	Erect tussock grass to 1 m tall	Perennial	H
<i>Digitaria ctenantha</i> (F.Muell.) Hughes	Erect tussock grass to 50 cm tall	Perennial	H
<i>Eriochloa crebra</i> S.T.Blake	• Erect tussock grass to 1 m tall	Perennial (approx. 2-3 years)	M to H
<i>Iseilema</i> spp. R.Br.	Erect tussock grass to 1 m tall	Annual/ephemeral	H
<i>Iseilema membranaceum</i> (Lindl.) Domin.	Semi-erect grass to 70 cm tall	Annual/ephemeral	H
<i>Iseilema vaginiflorum</i> Domin.	Semi-erect grass to 30 cm tall	Annual/ephemeral	H
<i>Malvastrum americanum</i> ** (L.) Torr.	Semi-erect grass to 70 cm tall	Perennial (possibly 2-5 years)	L
<i>Panicum</i> spp. L.	Erect forb to 50 cm tall	Perennial (approx. 5-8 years)	M to H
	Erect tussock grasses to 1.5 m tall		
<i>Panicum decompositum</i> R.Br.	Erect tussock grass to 1 m tall	Perennial	M
<i>Plantago</i> spp. L.	Erect forbs to 30 cm tall	Annual	H
<i>Plantago debilis</i> R.Br.	Erect forb	Annual	H
<i>Portulaca</i> sp. L.	Prostrate forb	Annual	M
<i>Rhynchosia minima</i> (L.) DC.	Prostrate (twining) legume	Perennial (approx. 2-3 years)	M
	Erect forb to 70 cm tall	Annual	L to M

<i>Iseilema</i> spp. R.Br.	Semi-erect grass to 70 cm tall	Annual/ephemeral	H
<i>Iseilema membranaceum</i> (Lindl.) Domin.	Semi-erect grass to 30 cm tall	Annual/ephemeral	H
<i>Iseilema vaginiflorum</i> Domin.	Semi-erect grass to 70 cm tall	Annual/ephemeral	H
<i>Malvastrum americanum</i> ** (L.) Torr.	Erect forb to 50 cm tall	Perennial (possibly 2-5 years)	L
<i>Panicum</i> spp. L.	Erect tussock grasses to 1.5 m tall	Perennial (approx. 5-8 years)	M to H
<i>Panicum decompositum</i> R.Br.	Erect tussock grass to 1 m tall	Perennial	M
<i>Plantago</i> spp. L.	Erect forbs to 30 cm tall	Annual	H
<i>Plantago debilis</i> R.Br.	Erect forb	Annual	H
<i>Portulaca</i> sp. L.	Prostrate forb	Annual	M
<i>Rhynchosia minima</i> (L.) DC.	Prostrate (twining) legume	Perennial (approx. 2-3 years)	M
<i>Salsola kali</i> L.	Erect forb to 70 cm tall	Annual	L to M
<i>Sida</i> spp. L.	Erect forbs to 1 m tall	Perennial	L
<i>Sida fibulifera</i> Lindl.	Prostrate, shrubby, forb	Perennial	L
<i>Sida filiformis</i> A.Cunn.	Erect forb to 50 cm tall	Perennial	L
<i>Sida trichopoda</i> F.Muell.	Erect forb to 60 cm tall	Perennial	L
<i>Solanum esuriale</i> Lindl.	Erect forb to 30 cm tall	Perennial	L

\* ranked as high (H), moderate (M) or low (L) palatability

\*\* cryptogenic species

changes in botanical composition (e.g. Orr 1980a, 1980b). This may be especially true at specific sites, and may be reflected in the deviations from the general pattern of change (represented by dashed lines in Fig. 2). For example, most sites within State A (1989) remained in this state until 1993 where drought conditions lead to the loss of *D. sericeum*. Some sites, however, went directly to State B in 1991. This deviation may have resulted from high grazing pressure at these sites and the subsequent removal of highly palatable *D. sericeum* plants. The change of sites from State B (1991) to State B (1993) and State A (1993) to State E (1994) may have resulted from high grazing pressure, with a decline in *Astrebla* spp. offset by an increase in less palatable plants or bare ground in each instance (Fig. 2). However, the shift of individual sites from State B (1993) to State D (1994) is difficult to explain. Whilst most bare ground sites were populated by *Amaranthus* spp. (generally regarded as a coloniser of bare ground), a few had high abundances of *Sida* spp. (generally regarded as a benign species), perhaps reflecting differing rainfall patterns, grazing pressure or initial soil seed banks.

Some individual sites had known grazing and rainfall histories that enabled the successful definition of disturbance gradients. For most sites, exact management practices (e.g. the timing and duration of grazing and numbers and types of animals) and rainfall data (e.g. timing and intensity of rainfall) which would have influenced changes were not recorded, necessitating the use of interpolated rainfall data and assumptions of grazing histories based on pasture measurements. A monitoring program which sought to fully involve land managers from the outset would have helped capture the detailed data required.

#### Generalised vegetation states

The generalised vegetation states (Fig. 3) represent a condensing (outside of ordination space) of the 20 date dependent states (Fig. 2) into a STM independent of time and rainfall, based on a consistent movement of sites and the existence of a degradation gradient at each sampling date. The continuity of sites dominated by *Astrebla* spp. for four out of five monitoring dates, across a range of seasonal rainfall patterns, provided evidence for the existence of one generalised *Astrebla* spp. dominated state (State I, Fig. 3). The continuity of sites with *Astrebla* spp. mostly dominant, but mixed with other species, provided evidence for the formation of State II.

Date specific grassland states were also associated with vegetation inseparable from the main groupings in ordination space (e.g. the *A. latifolia* sub-group, State B1 1989 to 1991 and State A1 1993). These are reflected as sub-groups within the generalised states. State I and State II were subdivided into two and four sub-groups, on the basis of the sub-dominance of *D. sericeum*, *A. latifolia*, *M. americanum*, bare ground or *Iseilema* spp. These generalised states are supported by evidence from McArthur *et al.* (1994) and Partridge (1996). State I is similar to a climax sere suggested by Roberts (1972) but at odds with some suggested pioneer species (e.g. *A. latifolia* and *Iseilema* spp.).

The general similarity between herbfield states identified under each set of seasonal circumstances (particularly the absence of perennial grasses) creates the temptation to form one generalised herbfield state. The lack of temporal species continuity, particularly with the separation of sites dominated by bare ground in May 1993 into three separate vegetation states in May 1994, provides insufficient evidence to justify this grouping. The evidence, instead, points to five separate vegetation states (States III through State VII) to be used within a monitoring framework. Pragmatically, a simplification to sub-groups within a single herbfield state ("State III") for presentation to range managers may be justifiable, if not strictly correct based on the evidence.

Some potential vegetation states were not identified over the monitoring period. One expectation from observations and anecdotal evidence was a *Salsola kali* dominant state similar to States IV or VI. Other dominant plants recorded in the literature include *Boerhavia diffusa* (under

State III

State II  
Grassland with *Astrebla* spp. mostly  
dominant  
State IIa

State I  
Grassland dominated by  
*Astrebla* spp.

... be especially true at  
 ... eral pattern of change  
 ... State A (1989) remained  
 ... *D. sericeum*. Some sites,  
 ... sulted from high grazing  
 ... *D. sericeum* plants. The  
 ... to State E (1994) may  
 ... offset by an increase in  
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 ... ractices (e.g. the timing  
 ... ll data (e.g. timing and  
 ... rded, necessitating the  
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... of ordination space) of  
 ... and rainfall, based on a  
 ... t at each sampling date.  
 ... monitoring dates, across a  
 ... ace of one generalised  
 ... with *Astrebla* spp. mostly  
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... comparable from the main  
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 ... These generalised states  
 ... 96). State I is similar to  
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... each set of seasonal  
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 ... particularly with the  
 ... arate vegetation states  
 ... The evidence, instead,  
 ... to be used within a  
 ... within a single herbfield  
 ... , if not strictly correct

... period. One expectation  
 ... ate similar to States IV  
 ... *Perhavia diffusa* (under

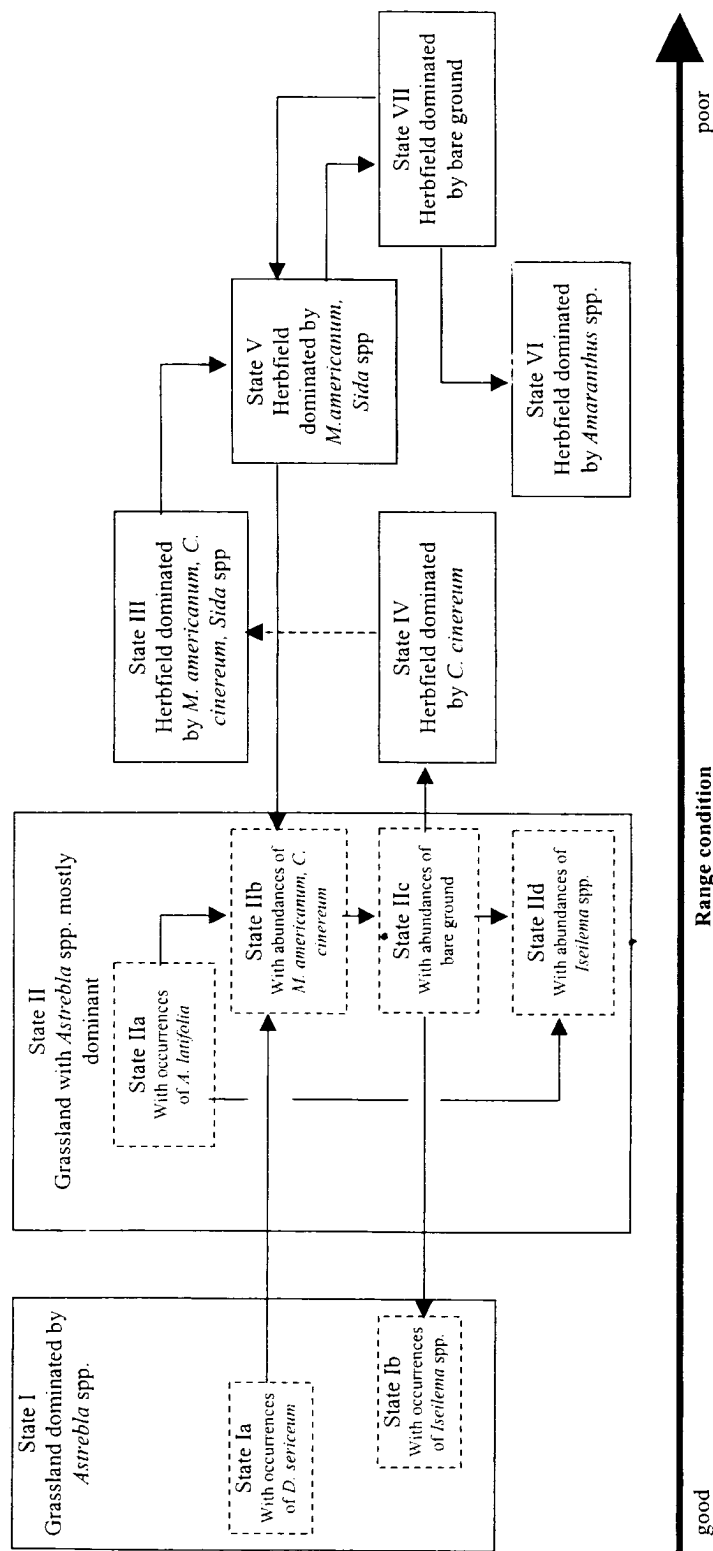
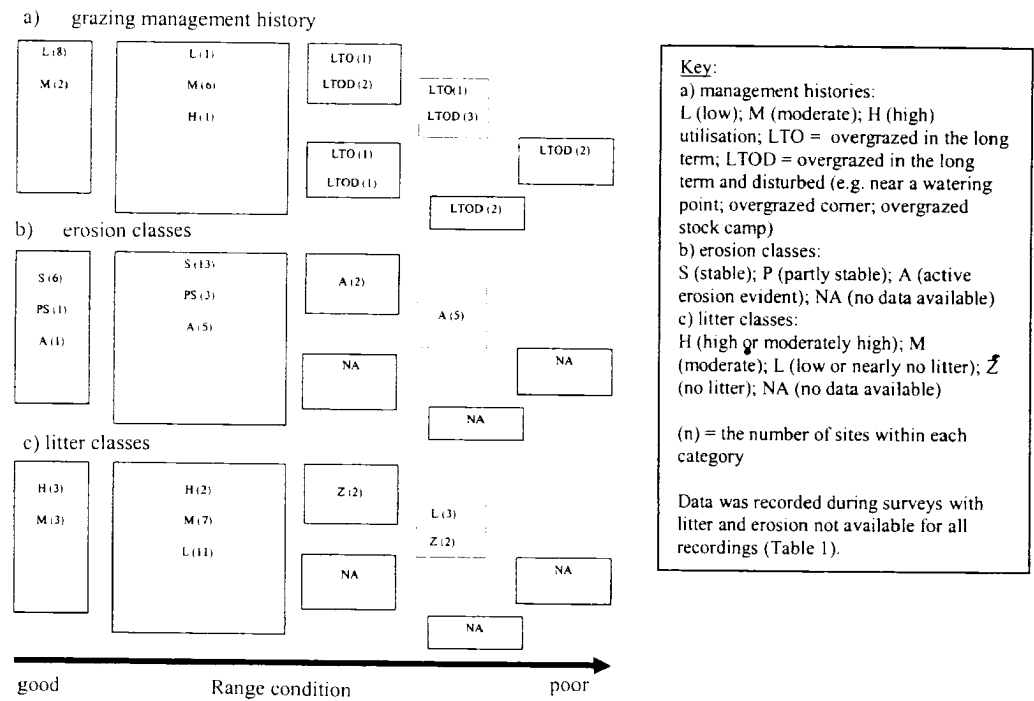


Fig. 3. A generalised, time independent, STM for the central Mitchell grasslands of Queensland, Australia, derived from pasture monitoring between August 1989 and May 1994. (Solid boxes represent well defined states, dashed boxes indicate sub-groups within states. Solid lines represent well defined Transitions; dashed lines indicate Transitions with weak supporting evidence. The horizontal separation of states reflects their relative position along the first ordination axis; vertical separation is for ease of presentation).

revision, *B. diffusa* is no longer valid in Australia), *Plantago debilis* and *Solanum esuriiale* (Davidson 1954). There is, however, insufficient evidence to include these plants within states in the current model. This suggests that a longer period of monitoring was required to capture a wider range of rainfall conditions and hence a fuller overview of the potential states within the central Mitchell grasslands. The emphasis should be placed on a time frame sufficient to capture a suite of different rainfall trends whilst being able to compare grazing management. Jones *et al.* (1995) suggested a minimum of 10 years when monitoring experimental grazing sites. Phelps *et al.* (1993) suggested monitoring 10 to 15 major climatic events over whatever time was necessary to encapsulate rainfall induced vegetation changes in the Mitchell grasslands.

*Identifying a degradation gradient*

The existence of a degradation gradient from State I (good condition) to State VII (poor condition) was tested through plotting known grazing histories, surface litter cover, erosion activity and bare ground within the generalised vegetation states of the proposed STM. It would be expected that declining ecological condition along a degradation gradient would be associated with factors such as increasing erosion resulting from increasing grazing intensity (expressed as utilisation) and the loss of soil surface cover. The lack of such a relationship would be sufficient to reject the presence of a degradation gradient, and to reject the proposed STM.



**Fig. 4.** Evidence for a degradation gradient within the STM for the central Mitchell grasslands: a) grazing management history; b) erosion classes; and c) litter classes.

The general trend present was for grazing intensity and erosion to increase and for surface litter levels to decline from State I to VII (Fig. 4). State I was dominated by sites with low utilisation (8 out of 10 of sites with known management histories), stable erosion (6 out of 8 sites) and high to moderate levels of litter (all sites). There were minor incidences of moderate utilisation and active erosion at sites within these vegetation states. State II was dominated by sites with moderate utilisation (6 out of 8 sites, with one low and one high), stable erosion (13 out of 21

sites) and moderate erosion (five sites) overgrazed in the stock camps and in present.

Other authors have in some cases, along *al.* (1994) presented placed along axes value of recognis (1994) presented speargrass zone, Restoration Thres effect change to domains of attract Kellner (1991).

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These examples i Clements (1916) stated. Specificall species are still p introduction of a attempts have not appropriate. This a

*Determining indic*

The definition of specific vegetation ordination axis. Th to reduce noise fro dates (e.g. rains f abundance and bel rainfall patterns (F abundances of all placement of new indicator species catalogue of states descriptions).

is and *Solanum esuriiale* these plants within states in was required to capture a potential states within the same sufficient to capture management. Jones *et al.* al grazing sites. Phelps *et* over whatever time was the grasslands.

ion) to State VII (poor face litter cover, erosion proposed STM. It would nient would be associated g intensity (expressed as ship would be sufficient d STM.

nt histories:  
 (moderate); H (high)  
 TO = overgrazed in the long  
 = overgrazed in the long  
 rbed (e.g. near a watering  
 ized corner; overgrazed  
 ases:  
 partly stable); A (active  
 at); NA (no data available)  
 s:  
 derately high); M  
 (low or nearly no litter); Z  
 A (no data available)  
 ber of sites within each  
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 on not available for all  
 ble 1).

al Mitchell grasslands:

se and for surface litter sites with low utilisation (out of 8 sites) and high moderate utilisation and minated by sites with e erosion (13 out of 21

sites) and moderate to low levels of litter (18 out of 20 sites). There were occurrences of active erosion (five sites). The herbfield states (States III to VII) exclusively contained sites that were overgrazed in the long term, or overgrazed and disturbed (those close to watering points, near stock camps and in overgrazed corners), were actively eroding and had low to zero surface litter present.

Other authors have deliberately ordered States and Transitions along degradation gradients, or in some cases, along two axes representing different aspects of degradation. For example, Ash *et al.* (1994) presented a model for northern Australian tropical tallgrass communities with States placed along axes for disturbance and risk of accelerated soil erosion. They also discussed the value of recognising key pasture species to indicate positive or negative change. Orr *et al.* (1994) presented two axes relating to degradation in their model for the southern black speargrass zone, animal productivity and soil stability. They also included a "Management Restoration Threshold" below which major alterations to management would be required to effect change to range condition. This threshold is similar in nature to the border between domains of attraction along a degradation gradient presented by Bosch (1989) and Bosch and Kellner (1991).

Grice and Macleod (1994), in a discussion on the practical use of STMs, ordered their model for the woodlands/grasslands of western New South Wales along a degradation gradient, albeit without defining the gradient as such. Jones and Burrows (1994) defined the relative degradation of states within their mulga zone STM, again suggesting the value of retaining this basic element of Clementsian theory. McIvor and Scanlan (1994) presented a model for the northern speargrass zone, in which transitions were acknowledged to be accompanied by changes in soil stability and pasture productivity. They did not define a degradation gradient although states were ordered in a way which could be interpreted as a degradation gradient. McArthur *et al.* (1994) explicitly divided their model for the Mitchell grass, bluegrass-browntop and Queensland bluegrass pasture zones into sustainable, deteriorating and degraded categories along a degradation gradient.

These examples indicate that whilst STMs are now well accepted in Australia, aspects of Clements (1916) and Dyksterhuis (1949) have been retained, albeit generally not explicitly stated. Specifically, perceived degradation gradients, management thresholds and key plant species are still presented as tools in interpreting range condition. This seems sensible. The introduction of a new system of modelling range condition should not mean all previous attempts have nothing to offer. Rather, the combining of the best elements of each would seem appropriate. This appears to be the unwritten intent of many rangeland researchers.

*Determining indicator species*

The definition of degradation gradients in both the generalised vegetation states and the time specific vegetation states made it possible to determine indicator species along the first ordination axis. The time specific vegetation states were initially analysed for indicator species, to reduce noise from differing rainfall patterns. Where rainfall patterns were similar at different dates (e.g. rains following a seasonal drought) similarities were also found in both species abundance and behaviour. This made it possible to summarise the indicator species according to rainfall patterns (Fig. 5). Whilst indicator species are presented individually, it is the combined abundances of all species which serve to group sites in ordination space. When assessing the placement of new sites relative to existing groups along the degradation gradient (i.e. states), all indicator species should be considered in the context of the descriptions included in the catalogue of states (see section "A quantitative State and Transition Model" for comprehensive descriptions).

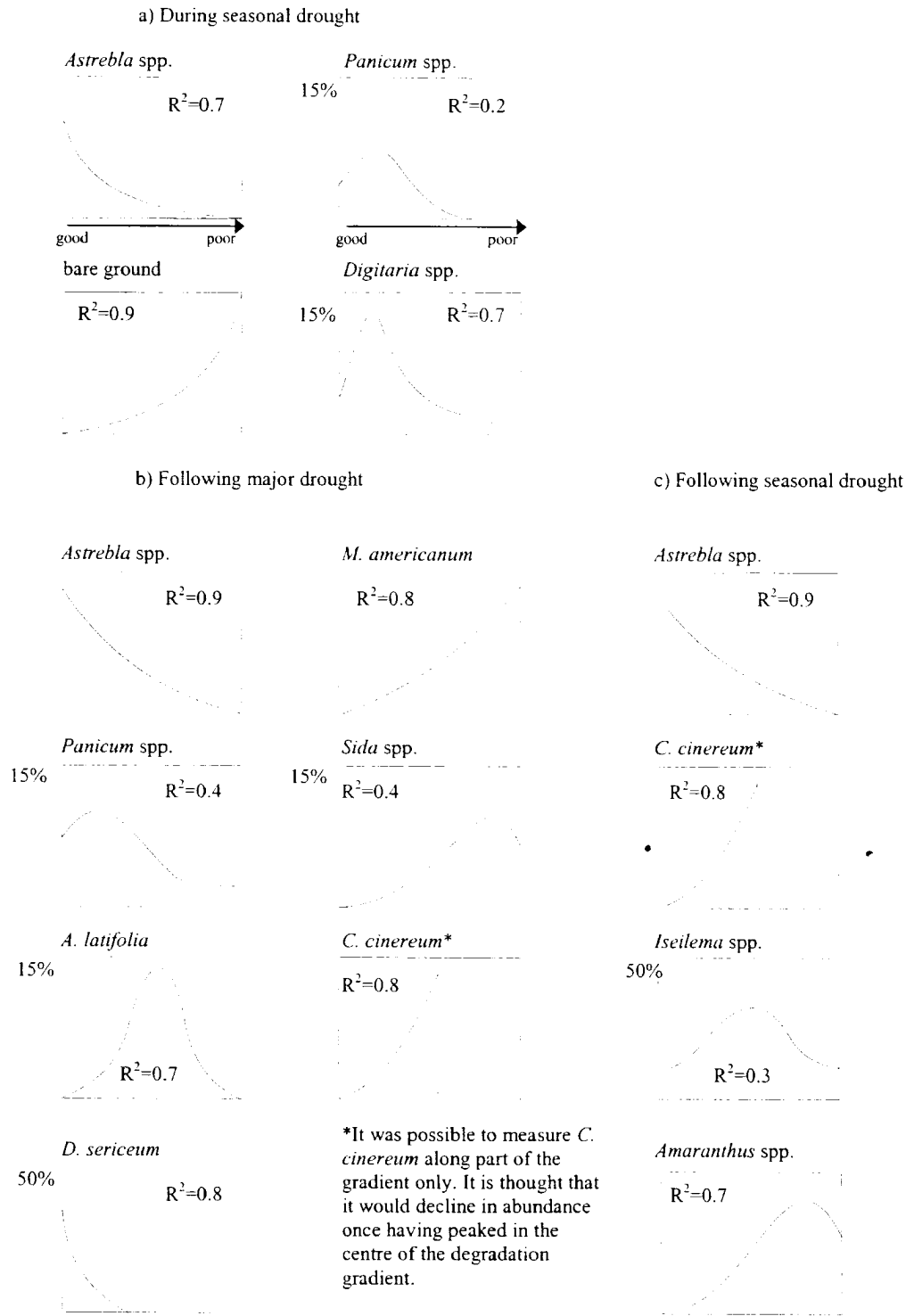


Fig. 5. Stylised response curves of indicator species along the degradation gradient (PCA axis one) for the central Mitchell grasslands within rainfall pattern groups: a) during seasonal drought; b) following major drought; and c) following seasonal drought. Maximum abundances (vertical axis) are 100% unless otherwise indicated.

During seasonal drought, the abundance of *Astrelba* spp. (a combination of *A. sericeum* and *A. latifolia*) was a moderate indicator of good range condition (e.g.  $R^2=0.7$ ) of non-degraded grasslands (a combination of *P. decompositum* and *P. polyanthemum*) of moderate abundance.

Analysis of the site following major drought, *Astrelba* spp. again had its highest abundance at the relatively high abundance of State Ia. The coefficient of determination was a good indicator of good range condition (an indication ( $R^2=0.9$ ) of the relative abundances of *A. sericeum* and *M. americanum* and *Panicum* spp. following major drought, contributing as an indicator of good range condition.

Following seasonal drought, the abundance of *Astrelba* spp. following favourable rainfall was a good indicator of the process of recovery of grasslands to good range condition, providing a good indication of the relative abundances of *C. cinereum* and *A. latifolia* following seasonal drought, and *Astrelba* spp. in these conditions in good range condition.

The ability to identify thresholds within the degradation gradient proportions as a guide to the proportions on botanical composition over time, representing the ability to extrapolate from the available data.

The concerns of incorporating seasonal and spatial and temporal variability in the coverage of temporal and spatial transitions.

*A quantitative State*

The identification of quantitative State Transition Matrix (STM) for the grasslands. Supplementing the defined and described states enhances information applicability and determining quantitative State Transitions has been undertaken on

During seasonal drought (Fig. 5a), bare ground was the strongest indicator ( $R^2=0.9$ ) of degraded range condition (equating to State VII of Fig. 3), while *Astrebula* spp. was the strongest indicator ( $R^2=0.7$ ) of non-degraded range condition (equating to States I and II). *Digitaria* spp. (a combination of *D. coenicola* and *D. ctenantha*) ( $R^2=0.7$ ) and *Panicum* spp. (primarily *P. decompositum*) ( $R^2=0.2$ ) were associated with State II at low abundances (Fig. 5) with high to moderate abundances of *Astrebula* spp. and low to moderate abundances of bare ground.

Analysis of the sites surveyed following drought-breaking rains (Fig 5b) indicated that *Astrebula* spp. again had its highest abundance in the non-degraded vegetation states (States I and II). The relatively high abundance of *D. sericeum* in association with *Astrebula* spp. was a good indicator of State Ia. The combined presence of *Astrebula* spp., *M. americanum* and *C. cinereum* was a good indicator of State II, forming State IIb under these circumstances. *Panicum* spp. provided an indication ( $R^2=0.4$ ) of State II, albeit only reaching low abundances (less than 10%). High abundances of *A. latifolia* distinguished State IIa within the overall confines of State II. Both *M. americanum* and *C. cinereum* were good indicators ( $R^2=0.8$ ) of the degraded forb states following major drought (particularly State III). *Sida* spp. abundances were less than 15%, contributing as an indicator ( $R^2=0.4$ ) of State III.

Following seasonal drought (Fig. 5c), *Amaranthus* spp. dominated State VI in response to favourable rainfall and is therefore a good indicator ( $R^2=0.7$ ) of severely disturbed states in a process of recovery. Sites in good condition were associated with high abundances of *Astrebula* spp., providing a good indicator ( $R^2=0.9$ ) for State I. Sites dominated by *Astrebula* spp. but with abundances of *C. cinereum* ( $R^2=0.8$ ) or *Iseilema* spp. ( $R^2=0.3$ ) indicated State II following seasonal drought, particularly States IIb and IIc. Other species associated with State II under these conditions included *Eriochloa crebra*, *Digitaria* spp. and *Sida* spp.

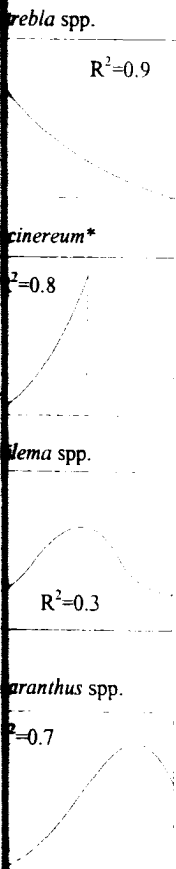
The ability to identify indicator species along a degradation gradient allows quantitative (using thresholds within ISPD, Bosch and Kellner 1991) or qualitative (using indicator species proportions as a guide) positioning of new sites into the central Mitchell grassland STM based on botanical composition and seasonal conditions. The use of indicator species from different times, representing a range of rainfall-induced botanical compositions, reduces the need to extrapolate from dissimilar seasons, and should provide a degree of certainty not previously available.

The concerns of Everist and Webb (1975) are thus partially satisfied through a model incorporating seasonal impacts, with a single recording event interpreted in context of both spatial and temporal variability. The prerequisite of success in this approach is adequate coverage of temporal variability, to ensure confidence in capturing all major vegetation states and transitions.

#### *A quantitative State and Transition Model (STM)*

The identification of vegetation states, degradation gradients and indicator species has allowed a quantitative STM to be developed (Fig. 3) and described (Box 1) for the central Mitchell grasslands. Supplementary information from other sources has allowed transitions to be better defined and described than from the pasture monitoring evidence alone. This new model enhances information previously presented by McArthur *et al.* (1994) by refining the area of applicability and utilising more recent evidence. This process could be considered useful in determining quantitative STMs in other rangeland ecosystems where monitoring programs have been undertaken or are current.

Following seasonal drought



on gradient (PCA axis  
s: a) during seasonal  
Maximum abundances

## Box I. Catalogue of States and Transitions for the central Mitchell grasslands

### Catalogue of States

*State I.* Grassland dominated by *Astrebula* spp., typically 50-90% relative abundance (50-70% during seasonal drought, 50-90% following seasonal or major drought). A stable state generally with low erosion, high litter, high projected foliage cover, high pasture yields (with a small forb yield component), drought dormant *Astrebula* spp. tussocks obvious but difficult to discern if living or dead. Animal productivity stable but may only be moderate due to a lack of forbs. State Ia exists only under better rainfall conditions, with *D. sericeum* relative abundances of 10-40%. State Ia generally exists following seasonal drought, with *Isotilema* spp. relative abundances of 10-15%.

*State II.* Grassland with *Astrebula* spp. mostly dominant, typically 5-50% relative abundance (5-50% during major drought, 15-50% following seasonal or major drought). A less stable state because of the lower perennial grass component, generally with low to moderate erosion, moderate to high litter, moderate to high projected foliage cover, moderate to high pasture yields (with a higher forb yield component), drought dormant *Astrebula* spp. tussocks may be obvious but difficult to discern if living or dead. Animal productivity fluctuates depending on rainfall but generally higher than State I because of a higher forb component. State IIa generally exists under better rainfall conditions with *A. latifolia* relative abundances of 5-15%. Paradoxically State IIa may be most apparent following seasonal drought before annual species occupy bare areas. State IIb generally follows drought or overgrazing, with *M. americanum* and/or *C. cinereum* relative abundances of 5-30%. State IIc generally occurs during drought with bare ground relative abundances of 10-30%. State IId generally occurs following drought with *Isotilema* spp. relative abundances of 10-30%. Animal production would be the lowest of State II (Lorimer 1978).

*State III.* Herbfield dominated by *M. americanum*, *C. cinereum* and *Sida* spp., typically 0-30% *Astrebula* spp. relative abundance. Identifiable from State V as *C. cinereum* relative abundance will be high (20-80%). A highly unstable state generally with moderate to high erosion, low to moderate litter, low to moderate projected foliage cover, low to moderate pasture yields (with a very high forb yield component), drought dormant *Astrebula* spp. tussocks not obvious. Animal productivity fluctuates widely depending on rainfall but generally low because of low grass component and inability to carry stock through drought conditions.

*State IV.* Herbfield dominated by *C. cinereum*, typically 0-30% *Astrebula* spp. relative abundance. Identifiable from State III as *C. cinereum* relative abundance will be high (20-80%) but *M. americanum* and *Sida* spp. will be low (less than 20%). A highly unstable state as per State III.

*State V.* Herbfield dominated by *M. americanum* and *Sida* spp., typically 0-20% *Astrebula* spp. relative abundance. Identifiable from States III and IV as *C. cinereum* is absent or present in minor abundances only (less than 10%). A highly unstable state as per State III.

*State VI.* Herbfield dominated by *Amaranthus* spp., typically 0-15% *Astrebula* spp. relative abundance. Generally exists following seasonal drought. A highly unstable state as per State III.

*State VII.* Herbfield dominated by bare ground, typically 0-10% *Astrebula* spp. relative abundance and a lack of other species. Generally exists during seasonal or major drought. Identifiable from State IIc as bare ground abundance is high (30-100%). A highly unstable state as per State III.

### Catalogue of Transitions

*Transition I, II.* (from State I to State II). Whilst not recorded, would occur with a reduction in *Astrebula* spp. density resulting from overgrazing, severe drought or possibly flooding or wildfire. Transition Ia, IIb would result from drought, unfavourable rainfall patterns or overgrazing which lead to a reduction in *D. sericeum* abundance.

*Transition II, I.* Not recorded but would occur with the recruitment of *Astrebula* spp. from at least 100 mm summer rainfall (Ausin and Williams 1988) with follow up rains coupled with high germinable seed banks. Only restricted by grazing under exceptional conditions. Transition IIc, IIb would result from summer rainfall conditions which favour *Isotilema* spp. recruitment. Transition IIa, IIb/Id would result from drought followed by early summer or summer rainfall favouring forb or annual grass recruitment. Transition IIb, IIc would result from drought reducing forb abundance, with IIc, IId following summer rainfall conditions favouring *Isotilema* spp.

*Transition II, III/IV.* Were not recorded, but would occur with a reduction in *Astrebula* spp. density coupled with winter and summer rainfall which favours forb recruitment. Transition IIc, IV specifically resulted from late winter rainfall which favoured *C. cinereum*.

*Transition IV, III.* There was only weak evidence for this transition, but resulted from an increase in *M. americanum* and *Sida* spp. following summer rainfall.

*Transition III, V.* Resulted from the loss of *C. cinereum*, probably due to unfavourable winter rainfall.

*Transition V, VII.* Resulted from the loss of *M. americanum* and *Sida* spp. during drought.

*Transition V, VII.* Resulted from the recruitment of *Astrebula* spp. and reduction in forbs

*Transition VII, V.* Resulted from the increase of *M. americanum* and *Sida* spp. following summer drought breaking rains.

*Transition VII, VI.* Resulted from the increase of *Amaranthus* spp. following summer drought breaking rains. The differences in transitions from State VII to either States V or VI are not clear. These species have only moderate to poor palatability so it is unlikely that grazing would affect their relative increase, which may depend only upon the timing of rainfall.

*Transition C. I. (from State I to State II)* - *Winters* not recorded, would occur with a reduction in *Astrelbia* spp. density resulting from overgrazing, severe drought or possibly flooding or wildfire. Transition Ia, IIb would result from drought, unfavourable rainfall patterns or overgrazing which lead to a reduction in *D. sericeum* abundance.

*Transition II. I.* Not recorded but would occur with the recruitment of *Astrelbia* spp. from at least 100 mm summer rainfall (Austin and Williams 1988) with follow up rains coupled with high germinable seed banks. Only restricted by grazing under exceptional conditions. Transition IIc, IIb would result from summer rainfall conditions which favour *Isoetes* spp. recruitment. Transition IIa, IIb/IIc would result from drought followed by early summer or summer rainfall favouring forb or annual grass recruitment. Transition IIb, IIc would result from drought reducing forb abundance, with IIc, IId following summer rainfall conditions favouring *Isoetes* spp.

*Transition II. III/IV.* Were not recorded, but would occur with a reduction in *Astrelbia* spp. density coupled with winter and summer rainfall which favours forb recruitment. Transition IIc, IV specifically resulted from late winter rainfall which favoured *C. cinereum*.

*Transition IV. III.* There was only weak evidence for this transition, but resulted from an increase in *M. americanum* and *Sida* spp. following summer rainfall.

*Transition III. V.* Resulted from the loss of *C. cinereum*, probably due to unfavourable winter rainfall.

*Transition V. VII.* Resulted from the loss of *M. americanum* and *Sida* spp. during drought.

*Transition V. VII.* Resulted from the recruitment of *Astrelbia* spp. and reduction in forbs

*Transition VII. V.* Resulted from the increase of *M. americanum* and *Sida* spp. following summer drought breaking rains.

*Transition VII. VI.* Resulted from the increase of *Amaranthus* spp. following summer drought breaking rains. The differences in transitions from State VII to either States V or VI are not clear. These species have only moderate to poor palatability so it is unlikely that grazing would affect their relative increase, which may depend only upon the timing of rainfall.

#### *Opportunities and Hazards*

The major hazard is overgrazing which leads to *Astrelbia* spp. abundances of less than 30%. Any of the herbfield states represent low productivity, increased erosion risk, the loss of desirable species and a real difficulty in returning to a desirable state. State VII is the worst in condition but, paradoxically, may return to State II more rapidly than the other herbfield states. The probability of this occurring, however, would be small with rains required to fall in a way that soil moisture is maintained over the whole of summer to enable *Astrelbia* spp. seedlings to reach maturity in the same summer. This has been observed in the northern Mitchell grasslands, and may not occur as readily in the herbfield states where soil moisture competition from mature forbs exists. Grazing management would have no impact on a massive recruitment, but continued heavy grazing would decrease the survival of the new mature tussocks. Similarly, newly matured *Astrelbia* spp. tussocks in the other herbfield states require light to moderate grazing to enhance growth and survival. It is at this stage that grazing management is crucial, with all of the evidence suggesting that rainfall alone drives recruitment events per se.

Opportunities exist within State II to optimise productivity by maintaining a balance of both perennial grasses and annual forbs and grasses. The type and quantity of annual species to grow will depend upon rainfall patterns and soil moisture, but the opportunity for their growth can be provided through reducing projected foliage cover (Orr 1980a) at moderate grazing pressures. Any increases in *M. americanum*, *C. cinereum* or *Isoetes* spp. should be treated with caution and grazing pressure reduced to enable pasture recovery. The major hazard to recovery is the long time frame which may be required before *Astrelbia* spp. recruitment occurs. Recovery following drought (e.g. State IIc) should also be accompanied with light grazing pressure to avoid the possibility of creating a herbfield state. If a projected foliage cover reduction strategy is adopted, standing dry matter is also reduced and drought susceptibility is increased. Observation suggests that most country is in State II, with some tending towards a herbfield state.

State I is the most stable, and provides a degree of drought proofing through high standing dry matter yields that is not found within State II. Whilst productivity may be lower than State II, income is generally more stable. For this reason, light grazing and fodder retention is a strategy practiced by many graziers in the central Mitchell grasslands.

#### *Allied situations*

The Mitchell grasslands occupy 45 million ha in Australia. States I and II could be expected to occur in all situations, but the herbfield states and sub-groups would vary, especially along the north-south summer rainfall gradient. Differences could also be expected towards the more arid western Mitchell grasslands where *Astrelbia* spp. density is typically lower. A band of looser ("ashy") soils with a fine ped structure, high porosity and strongly slaking surface run from the McInlay district through to the Muttaburra district in the north of Queensland. These soils may be associated with the Makunda (Klm) and Allaru (Kla) Formations of the Rolling Downs Group formed from Lower Cretaceous parent material (Vine 1970, Casey 1966, Casey 1968 and Vine 1963). Observation suggests *Astrelbia* spp. tussocks are more prone to dislodgment under drought and overgrazing in these ashy soils. These soils may also be more suited to *Isoetes* spp. growth.

### Implications of differing conditional states

Data presented in this paper indicate that the states can be arranged along a degradation gradient, with the best ecological condition at State I and the worst at State VII (Fig. 4). Direct observation, experience and other published evidence (Bushell *et al.* 1993, Phelps *et al.* 1993) suggest grazing, rainfall and vegetation data have been interpreted correctly in placing the herbfield states along the degradation gradient, although the spacing in Fig. 3 is not necessarily indicative of the relative severity of degradation of each state. It is likely that a management threshold exists between State II and the herbfield states (States III to VII), as few sites from latter states returned to a grassland state during the survey period. It is also likely that animal productivity in the herbfield states would be both reduced in the long-term and highly variable in the short-term.

The herbfield states, lacking perennial grasses, would have little feed on offer for livestock during dry periods. Perennial grasses comprise a significant proportion of the diet of sheep between (Lorimer 1978), as well as immediately following (Orr *et al.* 1988), pasture growth initiating rainfall events. This enables livestock to be carried longer into dry periods than pastures consisting of forbs alone would allow. However, animal nitrogen and energy balances may be lower on diets dominated by grasses (Norton *et al.* 1978, McMeniman *et al.* 1989), with forbs reported to have higher nutrient levels than green leaf of grasses (McMeniman *et al.* 1986). It is likely that animal productivity would vary considerably within the herbfield states and that a high risk of liveweight loss and animal mortality (or the need for agistment or supplementary feeding during drought) result.

The supposition that animal productivity is much reduced in states in the worst ecological condition (e.g. the herbfield states) is also supported by the findings of Roe and Allen (1993) and Phelps and Orr (1998). Both have reported that stocking sheep at levels which maintain good conditional states (i.e. moderate stocking rates) provided improved monetary returns over levels which lead to degraded states (i.e. high stocking rates) in the southern and northern Mitchell grasslands respectively.

### Mechanisms of transitions

As with states, not all expected transitions were identified during the study period and cannot easily be determined from the literature. For example, changes directly from State I to State II and State II to the herbfield states (e.g. State IV) were recorded only within sub-groups (there were transitions from State Ia to IIb and from State IIc to IV but transitions were not recorded from State I to II). Whilst such transitions may be expected, they are not presented within Fig. 3. Where there was clear evidence that a transition existed during the study period, it is represented as a solid arrow. Transitions with only weak evidence (e.g. only one or two sites which moved in that direction) are represented with a dashed line.

The mechanisms of transitions were not clear from the current study, with both the literature and observations used to define the processes involved. Any movement from good to poor condition would necessarily involve the loss of *Astrelba* spp. (Fig. 3 and Box 1). Orr (1975) cites the reasons for the depletion of *Astrelba* spp. in Mitchell grass pastures as:

- i) the removal of seedlings by gross overstocking;
- ii) excessive grazing during active growth;
- iii) grazing dormant plants close to ground level; and
- iv) burrowing for roots.

Within the context of variable rainfall, and associated variable pasture growth and botanical composition, i) would most likely occur following drought when the pasture biomass is low and there are few existing *Astrelba* spp. tussocks, or potentially over winter (Roe and Davies 1985);

ii) would most likely occur during  
iii) would most likely occur during  
likely occur during

Catastrophic climatic events, such as the loss of *Astrelba* spp. tussocks, large scale disappearance of tussocks, however, often occur as severe an impact on tussocks can be killed in summer can lead to extreme events. A catastrophic event t

Declining range cover of a net loss of *Astrelba* spp. new plants through (Roe 1975), and in maintenance of a *Astrelba* spp. tussock

Any improvement in (Fig. 3 and Box 1) summer rainfall patterns and Evenson 1991) moisture is maintained

It is unlikely that recruitment and yearling grazing, resulting in favour *Iseilema* spp. *Iseilema* spp. abundance within State II d c seedlings by gross following drought drought could there herbfield state, or p

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Other grasses and their dynamics are which were useful perennial forbs is germinable seed b grasses (Orr 1980) that space is rarely

- ii) would most likely occur during periods of below average rainfall or drought recovery;
- iii) would most likely occur during either winter or periods of drought; and iv) would most likely occur during periods of extreme drought.

Catastrophic climatic events, such as flooding, prolonged drought and wildfire may also lead to the loss of *Astrelba* spp. tussocks. Bowman *et al.* (1997) reported that flooding can lead to the large scale disappearance of *A. lappacea* in New South Wales. *A. squarrosa* and *A. elymoides*, however, often grow in flooded areas (Orr 1975), and flooding during dormancy may not have as severe an impact (personal observation). Williams and Roe (1975) reported that *Astrelba* spp. tussocks can be killed by drought, and local knowledge suggests that wildfire in the heat of summer can lead to the loss of *Astrelba* spp. Grazing management may also play a role in these extreme events. A transition from State I directly to a herbfield State would probably require a catastrophic event to reduce *Astrelba* spp. abundances from 50 to 90% to less than 30%.

Declining range condition could be avoided through the prevention of conditions which lead to a net loss of *Astrelba* spp., through either the protection of existing tussocks or the promotion of new plants through recruitment. Recruitment is generally both small and irregular (Williams and Roe 1975), and insufficient to compensate for high tussock mortality. This suggests that the maintenance of a site within either of the grassland states would be dependent on existing *Astrelba* spp. tussock survival.

Any improvement in range condition would necessarily involve a net gain of *Astrelba* spp. (Fig. 3 and Box 1) through rare large recruitment events, and depend upon both favourable summer rainfall patterns and a high germinable seed bank at the start of summer (Orr 1991, Orr and Evenson 1991), although seedlings recruited towards the end of summer may survive if soil moisture is maintained over winter (Austin and Williams 1988).

It is unlikely that differences in recruitment would exist between States I and II, as seedling recruitment and yearling mortality is higher under moderate grazing pressure than under no grazing, resulting in net similarities (Orr and Evenson 1991). However, if rainfall conditions favour *Iseilema* spp., recruitment of *Astrelba* spp. may be restricted (Orr and Evenson 1993). *Iseilema* spp. abundances reached 30% within State IId. Consequently, high grazing pressure within State IId could result in a transition to a herbfield state, similar to the removal of seedlings by gross overstocking. Orr (1980b) also suggested that the recovery of *Astrelba* spp. following drought depends largely upon recruitment. An increase in *Iseilema* spp. following drought could therefore reduce the proportion of *Astrelba* spp., potentially leading State IId to a herbfield state, or preventing State VII from recovering.

Populations of both *D. sericeum* and *A. latifolia* increase with above average summer rainfall (Blake 1938, Lee *et al.* 1980, Orr 1980a), the latter increasing mainly under lighter grazing pressure. As with *Astrelba* spp., their abundance is a result of recent rainfall history over the past one to three years (Orr 1981). A decline in *D. sericeum* and *A. latifolia* results from drought conditions. High grazing pressure may also reduce the abundance of the highly palatable *D. sericeum*. The Transitions of State Ia to State IIb and State IIa to State IIb or State IId resulted from dry conditions. The return of favourable rainfall at these sites would likely see the return of these sites to the compositions recorded in 1989.

Other grasses and forbs occupy the spaces between the tussocks of the perennial species and their dynamics are the most difficult to predict. This is reflected in the small proportion of forbs which were useful indicator species (Fig. 5). The abundance of the annual and short lived perennial forbs is a result of immediate rainfall history (Orr 1981) and dependent upon the germinable seed bank, the bare space available and the projected foliage cover of the perennial grasses (Orr 1980a). The low basal areas found in the Mitchell grasslands (1 to 6%) suggests that space is rarely limiting, although increases in the abundance of perennial grasses can be at

the expense of annual species (Orr 1981). Root competition from the perennial grasses may also limit moisture availability and restrict the abundance of annual species.

A wide range of annual forbs and grasses can be found following rains immediately after drought. Botanical composition under these conditions is determined by the timing of the rainfall e.g. *Daucus glochidiatus* and *Plantago* spp. respond to increased winter rainfall, whilst *Desmodium campylocaulon* and *Sida* spp. were recorded in highest abundance following summer rainfall (Orr 1981). *Iseilema membranaceum* was found to increase with increasing summer rainfall, as were *B. diffusa* and *Rhynchosia minima*. (Orr 1981, 1986). *M. americanum* increased with late or early summer rainfall (Orr 1986, Bushell *et al.* 1993, Phelps *et al.* 1993) but it survives for only two to three years before dying during dry or drought conditions.

Some forbs and annual grasses have been reported to occur only under different grazing pressures. Hall and Lee (1980) reported *Abutilon malvifolium*, *M. americanum*, *Portulaca* sp., *S. kali*, *Sida filiformis* and *C. cinereum* to occur only under heavy grazing with cattle in the northern Mitchell grasslands. Some *Sida* spp. were found to occur under both heavy and light grazing (e.g. *S. trichopoda*), but none were confined to light grazing alone. *Iseilema* spp. tended to increase under moderate grazing (Fig. 5). This is consistent with Foran and Bastin (1984) who reported *Iseilema vaginiflorum* density and biomass to be greater at 1.6 km than at either 0.8 or 3.2 km from water in a cattle grazing area, but differs from Hall and Lee (1980) who found that *Iseilema* spp. tended to increase under heavy grazing by cattle.

Transitions from and between any of the herbfield states are therefore difficult to predict. It is likely that the Transitions from State III to State V and from State V to State VII resulted from dry conditions and subsequent high forb mortality, rather than from grazing pressure. The formation of State IV, however, probably resulted from a combination of high grazing pressure, high *Iseilema* spp. density and rainfall conditions which favoured the germination of *C. cinereum*. The few sites which moved from State IV to State III probably received rainfall favouring the establishment of *M. americanum* and *Sida* spp. The Transition of State VII to either of States V or VI is probably dependent on rainfall patterns, similar to the findings of Orr (1981). The transition from State IIc to State Ib probably resulted from summer rainfall allowing *Iseilema* spp. to fill the bare spaces, but may have been accompanied by light grazing pressure. The return of any of the herbfield states to a grassland State would require the large scale recruitment of *Astrebla* spp., with a direct change from a herbfield State to State I very unlikely.

#### *Application of the central Mitchell grassland STM at the paddock scale*

The introduction of this paper asserted that "the successful implementation of sustainable best management practices ultimately rests with land managers". Whilst a quantitative STM has been developed to describe vegetation changes and their causes at specific sites, land managers require tools to monitor changes at relevant scales. In central western Queensland, the basic natural resource management unit is the grazed paddock, which ranges in size from small holding paddocks of 25 to 100 ha (used to infrequently hold stock for short periods of time during husbandry activities) to main paddocks of 2500 ha or greater. It is at this scale that land managers make decisions concerning stock numbers (grazing intensity), grazing initiation and grazing duration in relation to factors such as animal husbandry, market forces, labour supply and rainfall. It is thus at this scale that the largest impact on sustainability is realised.

In theory, paddocks can be mapped into conditional states within county types (e.g. Land Zones or Land Systems) using on-ground monitoring and remote sensing technology through GIS or paper-based cartography. For instance, Orr (1978, 1980a) defined grazing pressure and vegetation condition patterns through the on-ground monitoring of *Astrebla* spp. basal area and botanical composition in the Blackall district of Queensland. Bellamy *et al.* (1996) and Bastin *et al.* 1993 are two examples of the application of GIS and remote sensing technologies at the paddock scale to identify changes in vegetation states and grazing pressures for the interpretation of range condition. However, satellite technology has limitations in determining vegetation

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## Conclusions

State and Transition Models (Westoby *et al.* 1989) and the Clementsian based Degradation Gradient Method, which acknowledges the existence of thresholds (Bosch and Kellner 1991), were successfully combined to produce a quantitative STM for the central Mitchell grasslands of Queensland. Vegetation states were identified using ordination techniques and tracing the movements of individual monitoring sites through time. Similarities within these states across rainfall patterns allowed a generalised (temporally independent) model to be developed. Both the time specific and generalised vegetation states were found to occur along a degradation gradient. It was therefore possible to identify indicator species and to develop a STM which includes quantitative descriptors to place new sites within the predefined states. Using these two theories in combination it was possible to develop a tool by which land managers can interpret both current range states and transitions for monitoring sites on their own properties.

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## References

- Allen, W.J., Bosch, O.J.H., Gibson, R.G. and Jopp, A.J. (1995). Co-learning our way to sustainability: Integrating local and scientific knowledge through an evolutionary research approach to support land management decision-making. Proceedings 1st International Conference in MODSS for Agriculture and Environment, Honolulu, July 23-29.
- Ash, A.J., Bellamy, J.A. and Stockwell, T.G.H. (1994). Application of state and transition models to rangelands in northern Australia. *Trop. Grassl.* **28**: 223-8.
- Austin, M.P. and Williams, O.B. (1988). Influence of climate and community composition on the population demography of pasture species in semi-arid Australia. *Vegetatio* **77**: 43-9.
- Bastin, G.N., Sparrow, A.D. and Pearce, G. (1993). Grazing gradients in central Australian rangelands: ground verification of remote sensing-based approaches. *Rangel. J.* **15**: 217-33.
- Bastin, G.N., Tynan, R.W. and Chewings, V.H. (1998). Implementing satellite-based grazing gradient methods for rangeland assessment in South Australia. *Rangel. J.* **20**: 61-76.
- Belbin, L. (1987). PATN Pattern Analysis Package. CSIRO Division of Wildlife and Rangelands Research, February 1987.
- Bellamy, J. A., Lowes, D., Ash, A. J., McIvor, J. G. and MacLeod, N. D. (1996). A decision support approach to sustainable grazing management for spatially heterogeneous rangeland paddocks. *Rangel. J.* **18**: 370-91.
- Blake, S.T. (1938). The plant communities of western Queensland and their relationships, with special reference to the grazing industry. *Proc. R. Soc. Queensl.* **49**: 156-204.

- Bosch, O.J.H. (1989).  
 Bosch, O.J.H. and G  
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 Bosch, O.J.H. and K  
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 Bosch, O.J.H., Gauc  
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 QB82004. 10 pp.  
 Bushell, J.J., Reyno  
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 Proceedings of th  
 21, pp. 348-50.  
 Casey, D.J. (1966).  
 Bureau of Minera  
 Casey, D.J. (1968).  
 Bureau of Minera  
 Clements, F.E. (19  
 Carnegie Institute  
 Clements, F.E. (193  
 Davidson, D. (1954)  
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 Day, K.A. and Phi  
 pasture and land  
 Carter). Final P  
 DAQ124A pp. 31  
 Dyksterhuis, E.J. (1  
*Manage.* **2**: 104-1  
 Evans, R.A. and Lov  
*J. Range Manage*  
 Everist, S.L. and W  
 tropical closed fo  
 Science Report No  
 Fensham, R.J., Min  
 (2000). Broad-sca  
*Aust. J.Bot.* **48**: 27  
 Foran, B.D. and Bas  
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 Gauch, H.G. (198  
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 Glenn-Lewin, D.C.  
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our way to sustainability: approach to support land ODSS for Agriculture and sition models to rangelands position on the population Australian rangelands: ground d grazing gradient methods Wildlife and Rangelands 1996). A decision support land paddocks. *Rangel. J.* relationships, with special

- Bosch, O.J.H. (1989). Degradation of the semi-arid grasslands of southern Africa. *J. Arid Environ.* **16**: 143-7.
- Bosch, O.J.H. and Gauch, H.G. (1991). The use of degradation gradients for the assessment and ecological interpretation of range condition. *J. Grassl. Soc. South. Afr.* **8**: 138-46.
- Bosch, O.J.H. and Kellner, K. (1991). The use of degradation gradients for the ecological interpretation of range condition assessment. *J. Arid Environ.* **21**: 21-9.
- Bosch, O.J.H., Gauch, H.G., Booysen, J., Stols, S.H.E., Gouws, G.A., Nel, M.E. and Van Zyl, E. (1992). Integrated System for Plant Dynamics, Ver 1.0. Copyright (C) 1991, Dept. Plant and Soil Sciences, P.U. for CHE, Potchefstroom, South Africa.
- Bosch, O.J.H., Williams, J.M., Allen, W.J. and Ensor, A. (1996). Integrating community-based monitoring into the adaptive management process - the New Zealand experience. Proceedings of the Fifth International Rangeland Congress, Salt Lake City, July 23-28, Vol. II, pp. 105-6
- Bowman, A.M., Munnich, D.J., Chan, K.Y. and Brockwell, J. (1997). Factors associated with density of Mitchell grass pastures in north-western New South Wales. *Rangel. J.* **19**: 40-56
- Brown, J.R. (1994). State and transition models for rangelands. 2. Ecology as a basis for rangeland management: Performance criteria for testing models. *Trop. Grassl.* **28**: 206-13.
- Bruce, R.C. and Rayment, G.E. (1982). Analytical methods and interpretations used by the Agricultural Chemistry Branch for soil and land use surveys. Queensland Department of Primary Industries Bulletin QB82004. 10 pp.
- Bushell, J.J., Reynolds, J.A., Cowan, D.C., Phelps, D.G. and Milson, J.A. (1993). Effect of manipulative management options on a degraded pasture within the *Astrelba* spp. grazing lands of western Qld. Proceedings of the XVII International Grasslands Congress, New Zealand and Australia, February 18-21, pp. 348-50.
- Casey, D.J. (1966). 1:250,000 geological series - explanatory notes. Winton, Queensland. Sheet SF/54-12. Bureau of Mineral Resources, Geology and Geophysics, Canberra. 11 pp.
- Casey, D.J. (1968). 1:250,000 geological series - explanatory notes. Manuka, Queensland. Sheet SF/54-8. Bureau of Mineral Resources, Geology and Geophysics, Canberra. 13 pp.
- Clements, F.E. (1916). Plant succession: an analysis of the development of vegetation. Publication 242. Carnegie Institute; Washington. 512 pp.
- Clements, F.E. (1936). Nature and structure of the climax. *J. Ecol.* **24**: 242-84.
- Davidson, D. (1954). The Mitchell grass association of the Longreach district. University of Queensland paper, Department of Botany 3: 45-59.
- Day, K.A. and Philp, M.W. (1997). Appendix 3. Swiftsynd methodology. In: Evaluating the risks of pasture and land degradation in native pastures in Queensland. (Eds K.A Day, G.M. McKeon and J.O Carter). Final Project Report, Rural Industries Research and Development Corporation project DAQ124A pp. 31-2. Department of Natural Resources, Queensland. Internal Publication.
- Dyksterhuis, E.J. (1949). Condition and management of rangeland based on quantitative ecology. *J. Range Manage.* **2**: 104-15.
- Evans, R.A. and Love, R.M. (1957). The step point method of sampling, a practical tool in rangeland research. *J. Range Manage.* **10**: 208-12.
- Everist, S.L. and Webb, L.J. (1975). Two communities of urgent concern in Queensland: Mitchell grass and tropical closed forests. 2. National system of ecological reserves in Australia. Australian Academy of Science Report No. 19, pp. 39-52.
- Fensham, R.J., Minchin, P.R., Fairfax, R.J., Kemp, J.E., Purdie, R.W., McDonald, W.J.F. and Neldner, V.J. (2000). Broad-scale environmental relations of floristic gradients in the Mitchell grasslands of Queensland. *Aust. J. Bot.* **48**: 27-38.
- Foran, B.D. and Bastin, G. (1984). The dynamics of a Mitchell grass (*Astrelba* spp.) rangeland on the Barkly Tableland, Northern Territory. *Aust. Rangel. J.* **6**: 92-7.
- Gauch, H.G. (1982). 'Multivariate Analysis in Community Ecology'. Cambridge University Press, Cambridge. 298 pp.
- Glenn-Lewin, D.C. and van der Maarel, E. (1992). Patterns and processes of vegetation dynamics. In: Plant succession. Theory and prediction. (Eds D.C. Glenn-Lewin, R.K. Peet and T.T. Veblen) pp. 11-59. Population and community biology series 11. Chapman and Hall, London.
- Grice, A.C. and MacLeod, N.D. (1994). State and transition models as aids to communication between scientists and land managers. *Trop. Grassl.* **28**: 241-6.
- Hall, T.J. and Lee, G.R. (1980). Response of an *Astrelba* spp. grassland to heavy grazing by cattle and light grazing by sheep in north-west Queensland. *Aust. Rangel. J.* **2**: 83-93.
- Hardy, M.B. and Walker, R.S. (1991). Determining sample size for assessing species composition in grassland. *J. Grassl. Soc. South. Afr.* **8**: 70-3.
- Hill, M.O. and Gauch, H.G. (1980). Detrended correspondence analysis, an improved ordination technique. *Vegetatio* **42**: 47-58.

- Jones, P. and Burrows, W.H. (1994). A state and transition model for the mulga zone of south-west Queensland. *Trop. Grassl.* **28**: 279-83
- Jones, R.M., Jones, R.J. and McDonald, C.K. (1995). Some advantages of long-term grazing trials, with particular reference to changes in botanical composition. *Aust. J. Exp. Agric.* **35**: 1029-38.
- Lee, G.R., Orr, D.M. and Hall, T.J. (1980). The feathertop problem in Mitchell grass pastures. *Queensl. Agric. J.* **106**: 521-4.
- Lorimer, M.S. (1978). Forage selection studies. I. The botanical composition of forage selected by sheep grazing *Astrebula* spp. pasture in north-west Queensland. *Trop. Grassl.* **12**: 97-108.
- McArthur, S.R., Chamberlain, H.J. and Phelps, D.G. (1994). A general state and transition model for the Mitchell grass, bluegrass/browntop and Queensland bluegrass pasture zones of northern Australia. *Trop. Grassl.* **28**: 274-8.
- McIvor, J.G. and Scanlan, J.C. (1994). A state and transition model for the northern speargrass zone. *Trop. Grassl.* **28**: 256-9.
- McKeon, G.M., Hall, W.B., Crimp, S.J., Howden, S.M., Stone, R.C. and Jones, D.A. (1998). Climate change in Queensland's grazing lands. I. Approaches and climatic trends. *Rangel. J.* **20**: 151-76.
- McMeniman, N.P., Beale, I.F. and Murphy, G.M. (1986). Nutritional evaluation of south-west Queensland pastures. I The botanical and nutrient content of diets selected by sheep grazing on Mitchell grass and mulga/grassland associations. *Aust. J. Agric. Res.* **37**: 289-302.
- McMeniman, N.P., Beale, I.F. and Payne, G. (1989). The nutrient status of sheep grazing on a dry Mitchell grass pasture association in central-western Queensland. *Aust. Rangel. J.* **11**: 7-14.
- Milson, J. (1996). Plant identification in the arid zone. Department of Primary Industries, Queensland. Information Series Q194035. 104 pp.
- Milson, J. (2000). Pasture plants of north-west Queensland. Department of Primary Industries, Queensland. Information Series Q100015. 348 pp.
- Northcote, K.H. (1979). 'A factual key for the recognition of Australian soils (Fourth edition)'. Rellim Technical Publications Pty. Ltd. Adelaide, South Australia. 123 pp.
- Northcote, K.H., Hubble, G.D., Isbell, R.F., Thomson, C.H. and Bettenay, E. (1975). 'A Description of Australian Soils'. Commonwealth Scientific and Industrial Research Organisation, Australia. 170 pp.
- Norton, B.W., Murray, R.M., Entwistle, K.W., Nolan, J.V., Ball, F.M. and Leng, R.A. (1978). The nitrogen metabolism of sheep consuming Flinders grass (*Iseilema* spp.), Mitchell grass (*Astrebula* spp.) and mixed native pasture. *Aust. J. Agric. Res.* **29**: 595-603.
- Orr, D.M. (1975). A review of *Astrebula* (Mitchell grass) pastures in Australia. *Trop. Grassl.* **9**: 21-36.
- Orr, D.M. (1978). Effects of sheep grazing *Astrebula* grassland in central western Queensland. Master of Agriculture thesis, University of Queensland, Brisbane. 102 pp.
- Orr, D.M. (1980a). Effects of sheep grazing *Astrebula* grassland in central western Queensland. I. Effects of grazing pressure and livestock distribution. *Aust. J. Agric. Res.* **31**: 797-806.
- Orr, D.M. (1980b). Effects of sheep grazing *Astrebula* grassland in central western Queensland. II. Effects of seasonal rainfall. *Aust. J. Agric. Res.* **31**: 807-20.
- Orr, D.M. (1981). Changes in the quantitative floristics in some *Astrebula* spp. (Mitchell grass) communities in south western Queensland in relation to trends in seasonal rainfall. *Aust. J. Bot.* **29**: 533-45.
- Orr, D.M. (1986). Growth requirements and patterns of native forbs in Mitchell grass and mulga pastures. Report on terminated project WRTF K/2/1042. Department of Primary Industries, Queensland. Internal publication. 23 pp.
- Orr, D.M. (1991). Trends in the recruitment of *Astrebula* spp. in relation to seasonal rainfall. *Rangel. J.* **13**: 107-17.
- Orr, D.M. and Evenson, C.J. (1991). Effects of sheep grazing *Astrebula* grassland in central western Queensland. III. Dynamics of *Astrebula* spp. under grazing and exclosure between 1975 and 1986. *Rangel. J.* **13**: 36-46.
- Orr, D.M. and Evenson, C.J. (1993). A glasshouse study of competition between *Astrebula lappacea* (curly Mitchell grass) and two associated species. *Rangel. J.* **15**: 298-301.
- Orr, D.M., Evenson, C.J., Jordan, D.J., Bowly, P.S., Lehane, K.J. and Cowan, D.C. (1988). Sheep productivity in an *Astrebula* grassland of south-west Queensland. *Aust. Rangel. J.* **10**: 39-47.
- Orr, D.M. and Holmes, W.E. (1984). Mitchell grasslands. In: Management of Australia's rangelands (Eds G.N. Harrington, A.D. Wilson and M.D. Young) pp. 241-54. CSIRO Publishing, Melbourne.
- Orr, D.M., Paton, C.J. and McIntyre, S. (1994). A state and transition model for the southern black speargrass zone *Trop. Grassl.* **28**: 266-9.
- Partridge, I. (1996). Managing Mitchell grass: a grazier's guide. Department of Primary Industries, Queensland. Information Series Q196009. 42 pp.
- Phelps, D.G. (1999). Monitoring western Queensland's rangelands. Report on results from NLP project 90R520 An objective resource condition assessment method for western Queensland. Department of Primary Industries, Queensland. Information Series QO99019. 40 pp. + appendices.

Phelps, D.G. and Bates  
Proceedings of the  
Phelps, D.G., Bushe  
condition assessme  
Proceedings of the  
21, pp. 1924-7.  
Phelps, D.G. and Orr  
Mitchell grassland  
Department of Prim  
Roberts, B.R. (1972)  
Primary Industries.  
Roberts, G.O'B. and  
Department of Prim  
Roe, R. and Allen, G  
Pasture and wool  
*Rangel. J.* **15**: 302-  
Roe, R. and Davies, H  
Queensland. *Trop.*  
Stalmans, M. and Me  
the Northeastern T  
Tohill, J.C. and Gilli  
sustainability. *Trop.*  
Turner, E.J., McDon  
Study Part V. Dep  
Land Utilisation. 2  
Vine, R.R. (1963). I  
Bureau of Mineral  
Vine, R.R. (1970). I  
9. Bureau of Mine  
Watson, I.W., Burns  
model for manager  
Westoby, M., Walk  
equilibrium. *J. Ran*  
Whalley, R.D.B. (19  
change. *Trop. Gras*  
Williams, O B. and  
grasses in relation

Manuscript received

mulga zone of south-west  
 long-term grazing trials, with  
 1029-38.  
 Mitchell grass pastures. *Queensl.*  
 of forage selected by sheep  
 1-108.  
 and transition model for the  
 of northern Australia. *Trop.*  
 northern speargrass zone. *Trop.*  
 A. (1998). Climate change in  
 51-76.  
 of south-west Queensland  
 grazing on Mitchell grass and  
 pp grazing on a dry Mitchell  
 4.  
 Primary Industries, Queensland.  
 Primary Industries, Queensland.  
 (Fourth edition). Rellim  
 (1975). 'A Description of  
 in, Australia. 170 pp.  
 R.A. (1978). The nitrogen  
 (*Astrelba* spp.) and mixed  
*Trop. Grassl.* 9: 21-36.  
 tern Queensland. Master of  
 m Queensland. I. Effects of  
 m Queensland. II. Effects of  
*bla* spp. (Mitchell grass)  
 rainfall. *Aust. J. Bot.* 29: 533-  
 grass and mulga pastures.  
 stries, Queensland. Internal  
 rainfall. *Rangel. J.* 13: 107-  
 central western Queensland.  
 86. *Rangel. J.* 13: 36-46.  
 in *Astrelba lappacea* (curly  
 (1988). Sheep productivity  
 Australia's rangelands (Eds  
 ng, Melbourne.  
 the southern black speargrass  
 ent of Primary Industries,  
 results from NLP project  
 Queensland. Department of  
 indices.

- Phelps, D.G. and Bates, K.N. (1994). Estimating pasture yield in Mitchell grasslands using photostandards. Proceedings of the 8th Australian Rangeland Conference, Katherine, June 21-23, pp. 217-8.
- Phelps, D.G., Bushell, J.J. Bosch, O.J.H., Kent, D.J. and Beale, I.F. (1993). A system for objective condition assessment of *Astrelba* spp. pasture at the paddock level for better grazing management. Proceedings of the XVII International Grasslands Congress, New Zealand and Australia, February 18-21, pp. 1924-7.
- Phelps, D.G. and Orr, D.M. (1998). Determining rangeland response to drought and grazing in the northern Mitchell grasslands. Project DAQ120, final funding report to the International Wool Secretariat. Department of Primary Industries, Queensland. Internal publication. 33 pp. + appendices.
- Roberts, B.R. (1972). Ecological studies on pasture condition in semi-arid Queensland. Department of Primary Industries, Queensland. Internal publication. 126 pp. + appendices.
- Roberts, G.O'B. and Crouch, B. (ca. 1989). Client's needs identification in central western Queensland. Department of Primary Industries, Queensland. Internal publication. 11 pp.
- Roe, R. and Allen, G.H. (1993). Studies on the Mitchell grass association in south-western Queensland. 3. Pasture and wool production under different rates of stocking and continuous or rotational grazing. *Rangel. J.* 15: 302-19.
- Roe, R. and Davies, H.I. (1985). Long-term variation in the density of *Astrelba* spp. in the Warrego region of Queensland. *Trop. Grassl.* 19: 87-95.
- Stalmans, M. and Mentis, M.T. (1993). Development of monitoring procedures for the herbaceous layer on the Northeastern Transvaal escarpment. *Afr. J. Rangel. Forage Sci.* 10: 129-34.
- Tothill, J.C. and Gillies, C. (1992). The pasture lands of northern Australia. Their condition, productivity, and sustainability. Tropical Grassland Society of Australia. Occasional Publication No. 5. 106 pp.
- Turner, E.J., McDonald, W.J.F., Ahern, C.R. and Thomas, M.B. (1993). Western Arid Region Land Use Study Part V. Department of Primary Industries Technical Bulletin no. 30, published by the Division of Land Utilisation. 205 pp.
- Vine, R.R. (1963). 1:250,000 geological series - explanatory notes. McKinlay, Queensland. Sheet SF/54-7. Bureau of Mineral Resources. Geology and Geophysics, Canberra. 16 pp.
- Vine, R.R. (1970). 1:250,000 geological series - explanatory notes. Murrumbidgee, Queensland. Sheet SF/54-9. Bureau of Mineral Resources, Geology and Geophysics, Canberra. 21 pp.
- Watson, I.W., Burnside, D.G. and Holm, A.McR. (1996). Event-driven or continuous; which is the better model for managers? *Rangel. J.* 18: 351-69.
- Westoby, M., Walker, B. and Noy-Meir, I. (1989). Opportunistic management for rangelands not at equilibrium. *J. Range Manage.* 42: 266-74.
- Whalley, R.D.B. (1994). State and transition models for rangelands. I. Successional theory and vegetation change. *Trop. Grassl.* 28: 195-205.
- Williams, O B. and Roe, R. (1975). Management of arid grassland for sheep: plant demography of six grasses in relation to climate and grazing. *Proc. Ecol. Soc. Aust.* 9: 142-56.

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