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Temporary cropping in semi-arid shrublands increases native perennial grasses

Y. Alemseged[A,B], *R. B. Hacker*[A], *W. J. Smith*[A] *and G. J. Melville*[A]

[A]Industry & Investment NSW, Trangie Agricultural Research Centre, PMB 19, Trangie, NSW 2823, Australia.
[B]Corresponding author. Email: yohannes.alemseged@industry.nsw.gov.au

Abstract. Thickening of native shrubs is a major problem in many 'semi-arid woodlands' as significant increase in shrub density is often negatively correlated with herbaceous vegetation and leads to reduced pasture production and soil erosion. This project aimed to test the hypothesis that temporary cropping (up to three crops in 15 years) consistently increases the density of native perennial grasses following the removal of shrubs. A total of 30 paddocks that had been cropped during the last 20 years were randomly selected using a satellite-based database that documented annual clearing and cropping history from 1987 to 2003. Paddocks were classified into four types based on clearing and cropping history and grazing management – not cleared (shrubs), regrowth (re-invaded by shrubs), set stocked (cropped and grazed), light/rotationally grazed (cropped and grazed). The responses of vegetation and soil (chemical and physical) properties to clearing and cropping were evaluated. Results indicated that ground cover, native perennial grass cover and standing dry matter were highest under light/rotationally grazed conditions.

The shrub state represents a stable state within the Cobar pediplain brought about due to land-use change in the form of overgrazing and/or the removal of fire from the system. An alternative stable state was achieved as a result of disturbance in the form of clearing, cropping and grazing management thereby directly altering the shrub population. The resilience of this state is largely dependent on the grazing management system used and on the prevention of shrub from re-establishing while failure to control shrubs could lead to the re-emergence of the Shrub State. We conclude that native grasslands do regenerate following cropping after removal of shrubs. The importance of grazing management for restoring perennial ground cover following removal of shrubs and temporary cropping has been clearly demonstrated by the study.

Additional keywords: clearing, ground cover, pasture composition, seed bank, state and transition.

Introduction

Significant thickening of native shrubs in woodlands threaten the economic viability of pastoral businesses and can lead to soil erosion and potentially to a major shift in biodiversity (Witt *et al*. 2009). In New South Wales managements to reduce and hold shrub populations have been evaluated by research. Its impact on vegetation structure, pastoral productivity, land value and susceptibility of encroached landscapes to further degradation has been well documented (Harrington *et al*. 1984; Noble *et al*. 1984; Date 1987; Wilson and MacLeod 1991; Noble and Hodgkinson 1992; Noble 1997; Noble and Walker 2006).

Research over several decades has identified a range of management options that are capable of controlling shrubs including prescribed burning (Hodgkinson and Harrington 1985), mechanical clearing and chemical application (Noble *et al*. 2005; Noble and Walker 2006) but in most instances the cost is not justified by the economic benefit (e.g. Pressland 1981; Green 1989) and in some cases shrub density increases after existing shrubs are removed by ploughing (Daryanto and Eldridge 2010). The success of prescribed burning is also dependent on the build-up of fuel for effective burning (Noble *et al*. 1986). Grazing by goats may be a cost-effective means of control in some situations but not all invasive species are amenable to control in this way (Harrington 1979). Despite past research and the substantial efforts by some landholders (e.g. Hams 1992), there is a need to develop strategies that promote ecological restoration and militate against further harmful impacts (Dale *et al*. 2005).

Management of vegetation in New South Wales is controlled by Government policy. The *NSW Native Vegetation Act No. 103* (2003) allows shrubs to be managed, including removal of limited areas of scrub followed by temporary cropping, and return to native ground cover. While there is anecdotal evidence that native perennial grass species re-establish successfully in the post-cropping environment if seasonal conditions are favourable (G. Brooke, pers. comm.) other observations indicate that former cropping paddocks may support only further stands of shrubs. Noble *et al*. (1984) cautioned that accelerated erosion and salinisation can follow farming in marginal rangelands.

Some theoretical considerations suggest that re-establishment of native grasslands, post cropping, may require active

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management. Plant succession models, for example, suggest that establishment of early successional species such as annual forbs, rather than perennial grasses, are more likely following soil disturbance (Connell and Slatyer 1977). Changes in soil fertility as a result of cropping may influence the composition of the post-cropping plant community (Grime 1979). Higher levels of fertility, as might be promoted by crop fertilisation, have been shown by several studies to favour fast-growing competitive species (Chapman 2001), reduce species diversity (McCrea *et al.* 2004) or favour annuals over perennial grasses (Bolger and Garden 2002; Prober *et al*. 2005; Hacker *et al*. 2008). The development of 'islands of fertility' under shrub canopies (Schlesinger *et al*. 1990, 1996; Døckersmith *et al*. 1999) due to litter fall, soil accretion, and animal and fecal decomposition (Rhoades 1996) could result in nutrient distribution patterns which if persistent might favour re-establishment of trees or shrubs (Døckersmith *et al*. 1999) over native perennial grasses.

The aims of this study were to determine whether native perennial grassland returns following removal of shrubs and opportunistic cropping in the semi-arid woodlands of New South Wales, and to describe post-cropping vegetation dynamics in a state-and-transition framework (Westoby *et al*. 1989; Briske *et al*. 2005).

Materials and methods

Survey site identification

The study was conducted in western New South Wales, Australia (Fig. 1). Paddocks that had been cropped since 1987 were identified using a satellite-based database, a record of the clearing and cropping history of all paddocks based on annual satellite image interpretation and field verification (DL&WC 1999). Attributes of each paddock extracted from the database were 'year of first crop', 'number of crops' and 'years since last crop'. Thirty paddocks from 11 properties were selected for sampling (Fig. 1, Table 1) stratified by geographic location, number of crops, and years since last crop. The sample size ($n = 30$) was determined from preliminary modelling using botanical data from previous studies and assumptions regarding the expected changes in key variables in response to management, in order to achieve statistical power of 80% (i.e. an 80% probability of detecting a 10% change at the 5% level of significance).

Following paddock selection, landholders were contacted by telephone to obtain consent to undertake the field survey. All landholders consented to the field investigations and agreed to provide additional information at interview.

Paddocks were classified into four types based on cropping history (fertiliser and herbicide use) and grazing management. Paddocks (4) that were encroached with shrubs and had never been cleared, but were adjacent to a cropped paddock, were classified as 'shrub'. Paddocks (7) that were last cropped 10 years or more previously and were mostly reinvaded by shrubs were classified as 'regrowth'. Thirteen paddocks that had been cropped within the last 10 years and were set stocked when not in crop were classified as 'set stocked'. However, there were no stocking rate records available. The remaining six paddocks which had been cropped within the last 10 years and were either

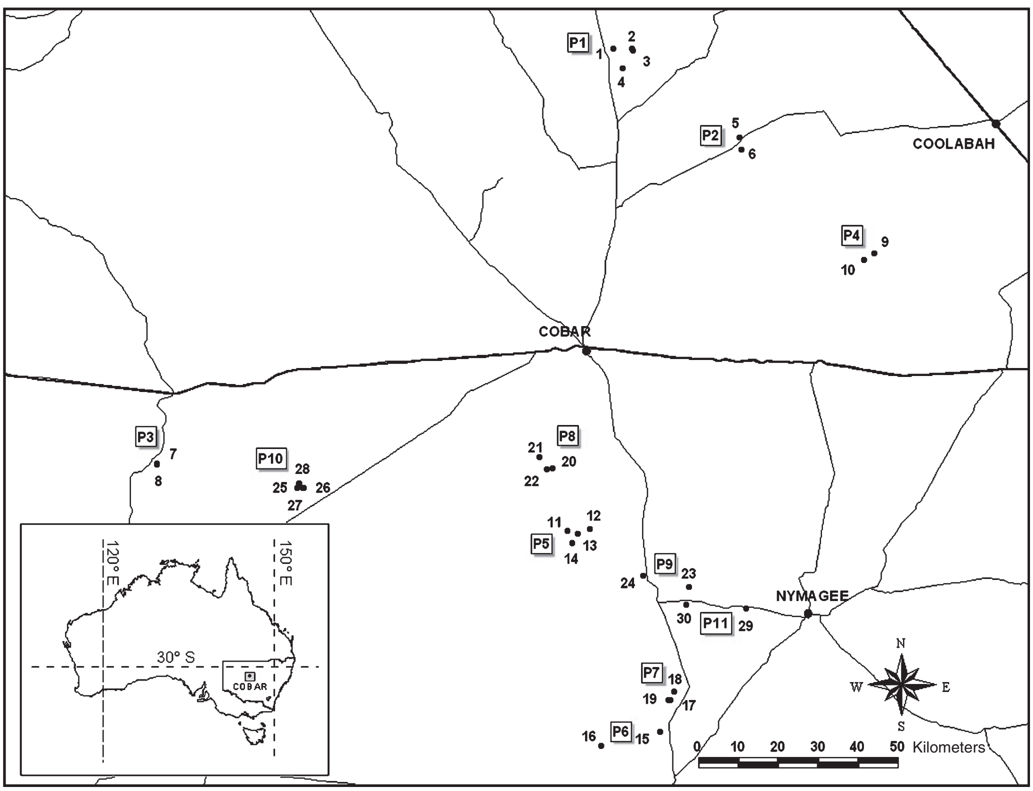

Fig. 1. Map showing the locations of paddocks that were surveyed. The location of Cobar is shown in the insert.

Table 1. Cropping history of 30 surveyed paddocks
Not cleared paddocks contain shrubs, regrowth paddocks have been cleared and the shrub has regrown, set-stocked paddocks have been cleared of shrubs, cropped and are now set stocked, light/rotational paddocks have been cleared of shrubs, cropped and are now lightly/rotationally grazed

Property number	Paddock number	Paddock type	Year cleared	Year first cropped	Year last cropped	Number of years since last crop	Years cropped
P1	1	Light/rotationally grazed	1992	1993	2006	1	3
P1	2	Regrowth	1988	1993	1993	14	1
P1	3	Set stocked	1988	2005	2005	2	1
P1	4	Set stocked	1988	2004	2006	1	2
P2	5	Light/rotationally grazed	1981	1999	2004	3	2
P2	6	Regrowth	1980s	–	1993	14	1
P3	7	Light/rotationally grazed	2006	2006	2007	0	2
P3	8	Shrub					0
P4	9	Regrowth	1970	1970	1984	23	2
P4	10	Set stocked	1998	1999	2005	2	2
P5	11	Set stocked	1985	1985	2007	0	2
P5	12	Set stocked	1986	1986	2006	1	5
P5	13	Set stocked	1994	1994	2005	2	5
P5	14	Set stocked	2002	Cleared in 2002 but never been cropped			
P6	15	Shrub					0
P6	16	Set stocked	2003	2004	2004	3	1
P7	17	Light/rotationally grazed	2003	2003	2007	0	5
P7	18	Light/rotationally grazed	2003	2003	2005	2	3
P7	19	Shrub					0
P8	20	Regrowth	1980	1980	2097	10	7
P8	21	Regrowth	1980s	–	1997	10	1
P8	22	Set stocked	1980s	–	1997	10	1
P9	23	Regrowth	1920	1920	1993	15	1
P9	24	Set stocked	1980s	1980s	2004	3	3
P10	25	Set stocked	1999	2000	2007	0	4
P10	26	Set stocked	1997	1998	2004	3	5
P10	27	Shrub					0
P10	28	Set stocked	1999	2000	2007	0	4
P11	29	Regrowth	1900	1900	1990	16	1
P11	30	Light/rotationally grazed	1985	1986	2007	0	5

rotationally (4) or lightly (2) grazed when not in crop were classified as 'light/rotationally grazed'. Rotationally grazed paddocks were managed using the time-controlled ('cell') grazing system while the lightly grazed paddocks were used intermittently as horse paddocks.

The impact of shrubs on the spatial distribution of chemical properties in the surface soil was also assessed on six separate paddocks on two properties. Separate paddocks were necessary to obtain the three categories in adjacent areas. The paddocks were designated as (1) shrub, or when they comprised grasslands that have not been encroached by shrubs as (2) grassland, and when the paddocks had been cropped in the last 3 years as (3) post-crop grassland. The properties were located 97 km south and ~100 km west of Cobar.

Data collection

Paddock surveys were conducted during March–April 2008, following a period of relatively high summer rainfall. Grassland condition was assessed by measuring ground cover, pasture botanical composition and standing dry matter (SDM) (non-woody vegetation). Ground cover and pasture composition were assessed using the Step Point Method described by Campbell and Hacker (2000). SDM and soil chemical properties were also assessed. Fertiliser (nitrogen, N) and herbicide used in each cropped paddock was recorded based on producer interviews.

Ground cover

Ground cover was surveyed along 10 parallel transects, each ~200 m in length, in each of the 30 paddocks. The starting point of the first transect was randomly determined by driving ~100 m perpendicular to the edge of the paddock. The position of this starting point was recorded using a hand-held GPS unit. Walking in a straight line for 200 m in a randomly chosen direction, the cover type directly below a drawing pin inserted in the toe of one boot was recorded as litter, grass butt, forbs, dung, wood, cryptogam or rock every four steps, generating 50 records per transect. At the end of each transect 30 steps were taken at a 90° angle to reach the starting point of the next transect which ran in the opposite direction. This process was repeated until 10 transects had been completed. Percent cover of each cover type, in each transect, was then calculated by multiplying the total number of 'hits' by two. Total cover for each transect was calculated by summing over all cover types.

Pasture botanical composition

The presence of plant species in a semi-circular quadrat of 0.5-m radius was recorded at each point used for ground cover determination (i.e. 50 points per transect) in the 30 paddocks. The quadrat was centred on the pin used for ground cover observations. Species frequency was calculated for each transect. Plant species were identified using the descriptions provided by Cunningham *et al*. (1992).

Standing dry matter

Non-woody SDM (kg DM/ha) in the 30 paddocks was assessed by comparing a photograph taken at the time of sampling with photo-standards contained in Campbell and Hacker (2000).

Soil chemical properties

General characteristics Soil chemical characteristics in each of the 30 paddocks surveyed were determined from five samples (0–10-cm depth) collected at 20-m intervals along a transect traversing the area from which vegetation data had been collected, and bulked. Bulked samples were analysed for 28 variables including pH ($CaCl_2$), organic carbon (OC), total N, cation exchange capacity, electrical conductivity (EC), colour and texture. Chemical properties were determined by the Incitec Nutrient Advantage analysis system (Incitec Pivot 2010).

Horizontal patterning

Relationships between shrubs and spatial distribution of chemical properties in the surface soil (0–10-cm depth) were assessed in paddocks from two additional properties. In the shrub paddocks 10 pairs of samples were collected, one from directly under a shrub canopy and the other mid way between the shrub and its nearest neighbour. The distance between samples in each pair was recorded. In the grassland and post-crop grassland, samples were again collected in pairs, the first at a random point and the second in a random direction from the first and at distances that matched all the 10 measured in the shrub paddocks. Individual soil samples were analysed for OC, total N, EC and pH by the Incitec Nutrient Advantage analysis system.

Statistical analysis

Most variables were analysed using general linear mixed models with ‘property’ and ‘property : paddock type’ fitted as random terms. Fixed effects in the models included ‘paddock type’ as defined above and ‘location type’ (for soil variables) which was classified as under shrub, between shrub, grassland or crop. Further details for each variable are given below.

Ground cover

Individual transect estimates of per cent cover for each of the categories listed above, as well as total cover, were subject to arc sin transformation and analysed using the mixed model:

$$\text{Ground cover} \sim \text{Paddock type} + \text{random}(\text{Property} + \text{Property} : \text{Paddock type}),$$

where Paddock type is fitted as a fixed effect and Property and Property : Paddock type are fitted as random effects.

Transects within paddocks are the basic units of measurement in this analysis which effectively assesses variation among paddock types in relation to variation among paddocks.

Botanical composition

Frequency of species in individual transects, expressed as a percentage, was summarised as a ‘mean occurrence’ (mean occ.) for each species in each paddock, subject to square root transformation, and analysed using the mixed model:

$$\text{Mean occ.} \sim \text{Paddock type} + \text{random}(\text{Property} + \text{Property} : \text{Paddock type}),$$

where Paddock type is fitted as a fixed effect and Property and Property : Paddock type are fitted as random effects.

In this analysis paddocks rather than transects are used as the basic unit of measurement, owing to the considerable number of transects which have zero occurrence.

A further analysis was also performed on botanical composition data to investigate the recent application of N (defined as N applied in 2007), using the mixed model:

$$\text{Mean occ.} \sim \text{Paddock type} * \text{N} + \text{random}(\text{Property}),$$

where Paddock type, N and their interaction are fitted as fixed effects and Property is fitted as a random effect.

Cumulative rainfall and years since last crop

Cumulative rainfall since last crop was derived for each paddock based on the summer (December–May) and winter (June–November) rainfall for the nearest official meteorological station. Mean occurrence for major species was then analysed, after square root transformation, using the mixed model:

$$\text{Mean occ.} \sim \text{Cum rainfall} * \text{Paddock type} + \text{random}[\text{spl}(\text{Cum rainfall}) + \text{Property} + \text{Property} : \text{Paddock type}],$$

where cumulative rainfall, Paddock type and the interaction term were fitted as fixed effects and Property, Property : Paddock type and a spline term for cumulative rainfall were fitted as random effects. The spline term allows for non-linear trends in cumulative rainfall. Uncleared paddocks were excluded from this analysis.

Since cumulative rainfall was highly correlated with years since cropping ($P > 0.97$) these effects could not be included in the one model. The effect of years since last crop on mean occurrence of species was therefore analysed separately using the mixed model:

$$\text{Mean occ.} \sim \text{years-since-cropping} * \text{Paddock type} + \text{random}[\text{spl}(\text{years-since-cropping}) + \text{Property} + \text{Property} : \text{Paddock type}].$$

Standing dry matter

SDM was analysed using the mixed model:

$$\text{SDM} \sim \text{Paddock type} + \text{random}(\text{Property} + \text{Property} : \text{Paddock type}),$$

where Paddock type is fitted as a fixed effect and Property and Property : paddock type are fitted as random effects.

Soil chemical properties

General characteristics: Soil variables were analysed using the mixed model:

$$\text{Soil var.} \sim \text{Paddock type} + \text{random}(\text{Property} + \text{Property} : \text{Paddock type}),$$

where Paddock type is fitted as a fixed effect and Property and Property : Paddock type are fitted as random effects. Each soil variable was analysed separately.

Horizontal patterning: Paddock types in the nutrient distribution study were characterised simply as shrub, grassland, or post-crop grassland and location types were characterised as 'grassland', 'post-crop grassland', 'under shrub' or 'between shrubs'. In the shrub paddocks there were 10 soil samples from each of the under shrub and between shrubs location types while data from 20 soil samples were available in the crop and grassland paddocks.

Soil variables were analysed using the mixed model:

$$\text{Soil var.} \sim \text{Location type} + \text{random}(\text{Property} + \text{Property} : \text{Location type}),$$

where Location type is fitted as a fixed effect and Property and Property : Location type within property are fitted as random effects.

To examine variability, essentially spatial distribution, of soil parameters in the various paddock types an absolute difference was calculated for each sample pair. These differences were examined using the mixed model:

$$\text{Diff.} \sim \text{Paddock type} + \text{random}(\text{Property}),$$

where Paddock type is fitted as a fixed effect and Property is fitted as a random effect.

In addition to the difference analysis, a variance components analysis was undertaken to examine variance between and within sample pairs (within paddock type). This was achieved using the random effects model:

$$\text{Soil var.} \sim \text{random}(\text{Property} + \text{Paddock type} : \text{Sample pair}),$$

with random terms for Property and Paddock type : Sample pair. The Paddock type : Sample pair term takes the form of a two-way separable variance structure which may be written:

$$D_p \otimes I_{20}$$

where D_p is a 3×3 diagonal matrix with diagonal terms equal to the between sample pair variances (one for each paddock type) and I_{20} is a 20×20 identity matrix for the 20 sample pairs in each paddock type (10 sample pairs from each property). The residual variance was modelled as a two-way separable variance structure using the form:

$$R_p \otimes I_{40}$$

where R_p is a 3×3 diagonal matrix with diagonal terms equal to the within sample pair (residual) variances (one for each paddock type) and I_{40} is a 40×40 identity matrix for the 40 samples in each paddock type (20 samples from each property).

Results

Rainfall

Monthly rainfall at Cobar for the period January 2007–April 2008 (Fig. 2) reflects the excellent summer season following extended dry conditions that determined the vegetation response recorded in the field surveys.

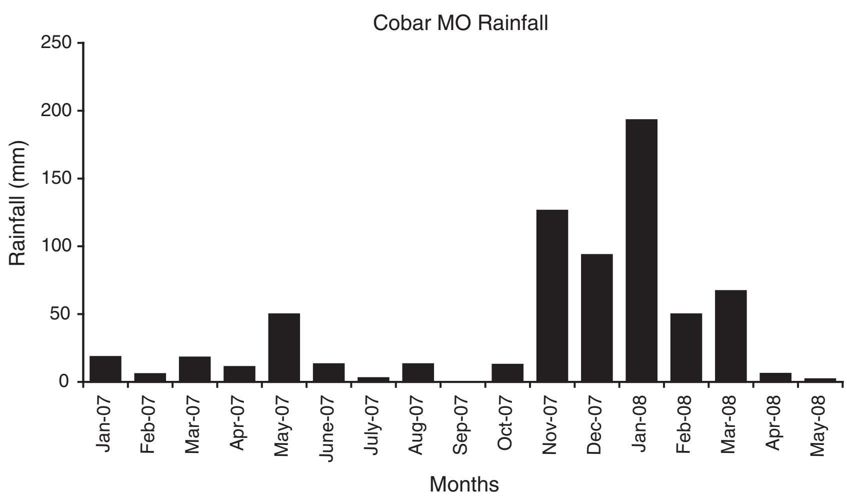

Fig. 2. Monthly rainfall before the study period, Cobar Meteorological Office (Station Number 048027, Bureau of Meteorology 2010).

Ground cover

Total ground cover was less than 30% and did not differ significantly between shrub regrowth and set-stocked paddocks, but was 50% in the light/rotationally grazed paddocks ($P < 0.001$; Fig. 3). Cover of native perennial grasses was more than 20% in the light/rotationally grazed paddocks compared with less than 5% in the other types of paddocks ($P < 0.01$) and was the major factor contributing to the difference in total ground cover between the light/rotationally grazed paddocks and the other paddocks (Fig. 3). Cryptogams, wood and rocks accounted for about half of the total ground cover in the shrub and regrowth paddocks (data not shown).

Botanical composition

Forbs, perennial grasses and copperburr (*Sclerolaena* spp.) were the major species groups that were related to paddock type (Fig. 4). Dense stands of native perennial grasses such as *Thyridolepis mitchelliana* (Nees) S.T.Blake (Mulga Mitchell grass), *Enteropogon acicularis* (Lindl.) Lazarides (Curly Windmill grass), *Eragrostis eriopoda* Benth. (woollybutt), *Eragrostis setifolia* Nees (neverfail), *Panicum* spp., and *Digitaria* spp. were recorded in paddocks that had been cleared of shrubs, then cropped and light/rotationally grazed. The frequency of less desirable species such as copperburr was significantly ($P < 0.01$) lower in paddocks that were set stocked following clearing and cropping, and particularly in paddocks that were light/rotationally grazed following cropping. The frequency of forbs was ~25% higher in paddocks that had been cleared and cropped ($P < 0.05$). Unlike the perennial grasses, however, the frequency of forbs did not differ between set-stocked and light/rotationally grazed paddocks (Fig. 4). Furthermore several of the set-stocked paddocks were observed to contain shrub seedlings (Fig. 5) which were not found in the light/rotationally grazed paddocks.

The relationship between N application in the cropping phase and botanical composition varied with post-cropping management and was statistically significant ($P < 0.001$). Ground cover of perennial grasses was reduced by N application when paddocks were set stocked ($P < 0.01$) but increased when paddocks were light/rotationally grazed ($P < 0.05$) (Fig. 6). Ground cover of forbs was not related to N application.

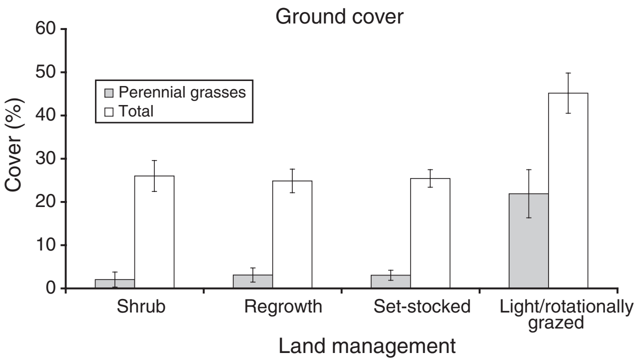

Fig. 3. Total cover and perennial grass ground cover (%) under the different land management categories based on clearing and cropping history and grazing management. Shrub paddocks contain shrubs, regrowth paddocks have been cleared and shrubs have regrown, set-stocked paddocks have been cleared of shrubs, cropped and subsequently set stocked, light/rotationally grazed paddocks have been cleared of shrubs, cropped and subsequently lightly/rotationally grazed. Error bars represent ± one standard error from the predicted ground cover %.

Standing dry matter

SDM varied from ~100 kg/ha in both shrub and regrowth paddocks to ~300 kg/ha in set-stocked paddocks and 1100 kg/ha in light/rotationally grazed paddocks ($P < 0.001$) (Fig. 7).

Cumulative rainfall and years since last crop

Cumulative rainfall and year since last crop did not have significant effect on ground cover, botanical composition or SDM.

Soil nutrient content

Of the 28 variables analysed only OC (%) was significantly related to post-cropping management (Fig. 8). Both light/rotationally grazed and set-stocked paddocks had higher OC than shrub and regrowth paddocks but the difference was significant ($P < 0.05$) only for the light/rotationally grazed paddocks.

Soil nutrient distribution

Soil OC, pH ($CaCl_2$) and total N were significantly higher ($P < 0.001$) under shrubs than between shrubs and soils were significantly more acidic ($P < 0.001$) away from shrubs, in cropped paddocks and in open grasslands than directly under the shrub canopies.

Organic carbon displayed much larger differences between paired samples in the shrub land paddocks compared to either the crop or grassland paddocks ($P < 0.001$). This same trend was also evident for total N ($P < 0.001$), EC ($P = 0.05$) and pH ($CaCl_2$) ($P < 0.01$). For OC, EC, pH ($CaCl_2$) and pH (water), paired sample differences were similar in the crop and grassland paddocks. (Table 2)

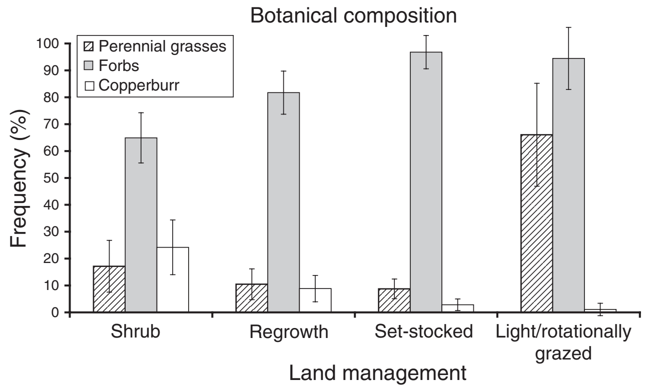

Fig. 4. Frequency of the major pasture components that were significantly related to the land management practices. The perennial grasses include Mulga Mitchell grass, Curly Windmill grass, woollybutt, neverfail, *Panicum* spp. and *Digitaria* spp. Error bars represent ± one standard error from the predicted frequency. Shrub paddocks contain shrubs, regrowth paddocks have been cleared and shrubs have regrown, set-stocked paddocks have been cleared of shrubs, cropped and subsequently set stocked, light/rotationally grazed paddocks have been cleared of shrubs, cropped and subsequently lightly/rotationally grazed. Error bars represent ± one standard error from the predicted ground cover %.

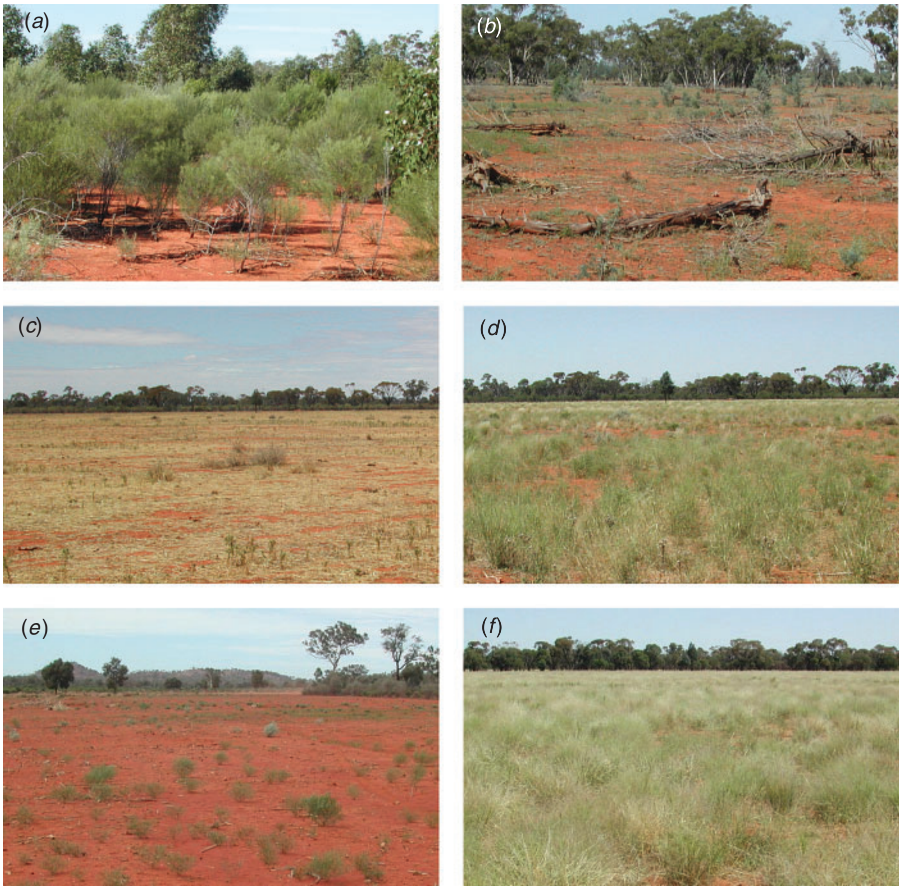

Fig. 5. Photos illustrating the different possible outcomes of temporary cropping as a means for restoring perennial grassland. (*a*) Represents shrub-dominated area identified as State I in the state and transition model; (*b*) paddocks that were cleared but not cropped (State II in the model) are reinvaded by shrubs and ground cover is dominated by wood debris; (*c*, *d*) photos of the same paddock taken in November 2007 and March 2008, respectively. These photos show the importance of ground cover for positive response to rainfall and are examples of State III; (*e*) In contrast paddock E did not respond to the rainfall as there was little herbaceous ground cover as a result of overgrazing and it is being reinvaded by shrubs after the 2007–08 summer rain (transition 4); and (*f*) it shows a rotationally grazed post-cropping paddock that contains several of the desirable perennial grasses (State IV in the model).

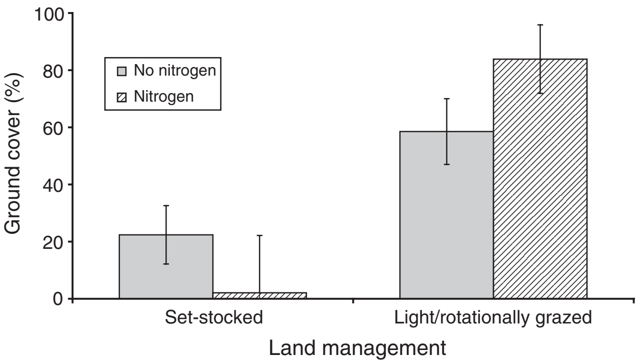

Fig. 6. The effect of nitrogen application on the perennial grass cover under set-stocked and light/rotational grazing management systems. Error bars represent ± one standard error from the predicted ground cover %. Set-stocked paddocks have been cleared of shrubs, cropped and subsequently set stocked, light/rotationally grazed paddocks have been cleared of shrubs, cropped and subsequently lightly/rotationally grazed.

These results were confirmed by the variance components analysis which revealed larger within pair variances in the shrub land paddocks than the other paddock types for each of the soil variables which were studied, especially OC.

Discussion

While successional models (e.g. Connell and Slatyer 1977) predict the dominance of early successional species in the years immediately following cropping, our study showed that native perennial grasses were able to re-establish quickly in the post-cropping period with effective grazing management. Indeed, perennial grasses established in large numbers in the first year after cropping in paddocks which were rotationally grazed or only lightly stocked following cropping. Species such as Mulga Mitchell grass, Curly Windmill grass, woollybutt, neverfail, *Panicum* spp. and *Digitaria* spp. were dominant in six paddocks spread over five properties where this management system was applied.

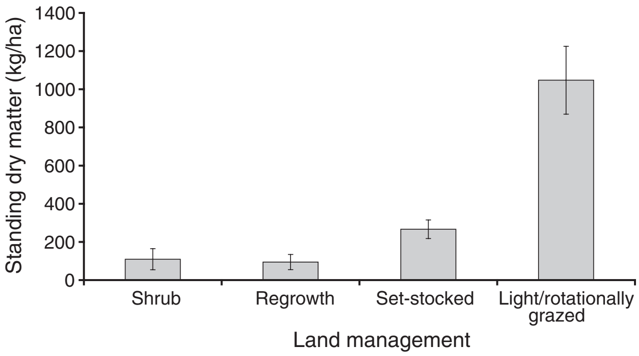

Fig. 7. Standing dry matter (SDM) (non-woody only) under the four land management practices. Error bars represent ± one standard error from the predicted SDM. Shrub paddocks contain shrubs, regrowth paddocks have been cleared and shrubs have regrown, set-stocked paddocks have been cleared of shrubs, cropped and subsequently set stocked, light/rotationally grazed paddocks have been cleared of shrubs, cropped and subsequently lightly/rotationally grazed. Error bars represent ± one standard error from the predicted ground cover %.

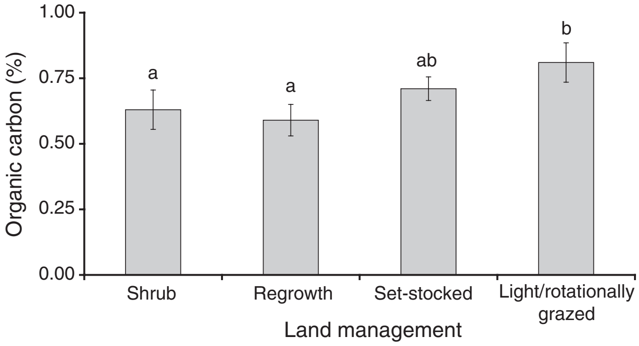

Fig. 8. Soil organic carbon (%) (0–10 cm) under the four land management practices – those with the same letter are not significantly different at the 5% level. Error bars represent ± one standard error from the predicted organic carbon %. Shrub paddocks contain shrubs, regrowth paddocks have been cleared and shrubs have regrown, set-stocked paddocks have been cleared of shrubs, cropped and subsequently set stocked, light/rotationally grazed paddocks have been cleared of shrubs, cropped and subsequently lightly/rotationally grazed. Error bars represent ± one standard error from the predicted ground cover %.

Table 2. Paired sample differences – each figure in the Table represents the mean absolute differences between the sample pairs in the post-crop grassland, uncropped grassland and shrub land as predicted by the model

Variable	Post-crop grassland	Grassland	Shrub	*P*-value
pH (water)	0.325	0.320	0.460	n.s.
pH ($CaCl_2$)	0.325	0.350	0.615	<0.01
EC (dS/m)	0.024	0.021	0.041	0.05
Total N (%)	0.011	–	0.037	<0.001
OC (%)	0.073	0.097	0.367	<0.001

The size of a seed bank is primarily determined by the dormancy mechanisms and the intrinsic capacities of seed survival of the composite species (O'Connor 1991). Hodgkinson *et al.* (1980) reported 'seed bank' decline of major grass species in *Eucalyptus populnea* woodland most likely due to seed death (decay) and predation, although despite the decline, seeds of the common species were still present after a year of no new addition. Silcock and Smith (1990) demonstrated that germinability of some of the perennial grass species recorded in this study reached very low levels after 1–3 years and suggested that many of the valuable grass species need to set seed frequently to retain adequate seed bank for regeneration after drought. The presence of these species in this study demonstrated that this did not occur under the conditions of the study and suggests sufficient viable seed remained in the soil for the marked response observed under the favourable seasonal conditions. The presence of the soil germinable seed bank in our study may have resulted from the sheltering of seeds under the hard setting soil surface from light and moisture, the two requirements for germination. Light, like water, is required for germination (Grime 1981) and burial causes inhibition of germination thereby creating the seed bank. Alternatively the intrinsic capacity of survival of these species could have contributed to the presence of viable seed.

The combination of soil disturbance by removal of the shrubs and by cultivation for cropping, which presumably facilitated infiltration, and the adequate spring–summer rainfall preceding the survey, probably account for the response observed. J. Bean (pers. comm.) found that landscape function, which was modified by pitting, was much more important than seed supply in determining the rate of regeneration of degraded semi-arid woodland in the general study area. In addition, physical or chemical suppression from shrubs and/or litter could have prevented the germination of grasses in uncleared (shrub) paddocks (Tighe *et al.* 2009). The removal of shrubs may therefore have contributed directly to the re-establishment of grasses.

Our results have important implications for the re-establishment of native perennial grasses following shrub management. The study has shown that seeding with native grasses following removal of shrubs and temporary cropping is not required, at least in the circumstances of this study. This may have important implication in reducing the cost of regenerating native perennial grasses in semi-arid regions by removing the need for grass seed and specialised seeding equipment. Further work would, however, be useful to determine whether seeding with native grasses is rarely or never required following shrubs treatment and cropping, or whether there are circumstances in which seeding is required to restore native perennial ground cover.

The lower cover of native perennial grasses in set-stocked paddocks with applied N is in line with expectations. This is because higher levels of soil fertility have been shown to favour fast-growing annual species (Bolger and Garden 2002; Prober *et al.* 2005; Hacker *et al.* 2008). However, reasons for the higher cover of native perennials with N application under light/rotational grazing compared with set stocking are not clear. The combination of N application and light/rotational grazing may have had the dual benefits of promoting seed production from the perennials that first established after cropping, providing a larger perennial soil seed pool for the current seasonal response, and reducing competition from annuals due to the higher densities achieved.

The re-establishment of scrub observed in paddocks that were heavily grazed and devoid of ground cover (Fig. 5*e*) is consistent with other reports of shrub regeneration following clearing (e.g. Pressland 1981; Booth *et al*. 1996*a*; Daryanto and Eldridge 2010). Harrington and Johns (1990) reported up to 700% decrease in herbaceous biomass due to re-establishment of cleared shrubs and woody plants in eucalyptus savanna woodland ~16 years after clearing. In the absence of competition from good perennial grass cover, shrub seedlings germinate and grow as seasonal conditions permit and their control will ultimately incur significant cost or require additional clearing and cropping. Harrington (1991) showed that *Dodonaea attenuate* seedling survival was inversely related to the amount of herbaceous growth. With good perennial grass cover shrub seedlings face competition and are likely to be eliminated in the first summer following establishment (e.g. Harrington *et al*. 1984; Booth *et al*. 1996*b*).

Appropriate post-cropping management of paddocks is thus essential if the benefits of the cropping phase are not to be lost. Apart from appropriate grazing management, it might be desirable to sow a crop in regenerated paddocks every few years with minimal disturbance to soil and ground cover using the principles of 'pasture cropping' (Millar and Badgery 2009). This involves the direct drilling of a winter cereal into dormant summer-growing pasture. If shrub seedlings are present this will increase competition and provide ground cover throughout the year, while providing additional grazing, and possibly a harvested crop if seasonal conditions are favourable.

Total ground cover was influenced by the proportion of perennial grass cover which was in turn determined by the grazing management system. Murphy and Lodge (2002) recognised ground cover (either living plants or plant litter) as a key indicator of 'rangeland sustainability' and several reviews in the semi-arid woodlands have emphasised its importance for control of infiltration, run-off and soil erosion (e.g. Hodgkinson and Freudenberger 1997; Tongway and Ludwig 1997). Restoration of native perennial grasslands can thus be expected to improve ecological processes resulting in more productive and resilient landscapes.

Spatial variability in soil nutrients on a scale comparable to that observed under shrubs was not evident in either the open grassland or the cropped paddocks. Most of the variation observed occurred between locations within the shrub paddocks (under *v.* between shrubs) and could be accounted for by litter fall. Soil chemical patterns that exist under shrubs appear to break down rapidly under cropping, at least for the constituents measured here, and impose no limitation on perennial grass regeneration.

Our understanding of the dynamics of the system described above is summarised in the state-and-transition diagram in Fig. 9 and illustrated in Fig. 5. We have identified four distinct alternative states including the shrub state. The three states are results of management intervention in the form of clearing, cropping and grazing management, each of which could revert back to the shrub state unless managed properly. Another stable state, 'open woodland', is not included in the discussion as the main focus of this study is managing shrubs using temporary cropping and there is no proposal to crop on open woodlands.

Catalogue of states

State I. Shrub

(1) Shrub (*Eremophila* spp., *Cassia* spp., *Dodonaea* spp.),
(2) Dense to scattered *E. populnea* F.Muell. and/or *Callitris* spp.,
(3) Perennial grass cover less than 2%.

State II. Annual forbs and grasses

(1) Few perennial grasses,
(2) Ground cover dominated by wood debris,
(3) Shrub seedlings,
(4) In the absence of proper management most likely to revert to State I within 10–15 years.

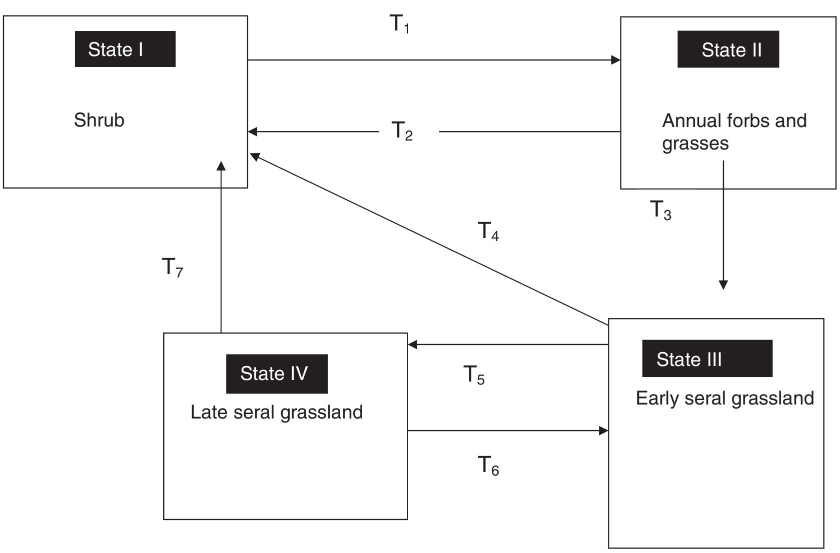

Fig. 9. State and transition model of vegetation dynamics in vegetation of the Cobar pediplain.

State III. Early seral grassland

(1) State between cropping phases,
(2) Crops mainly wheat and oats,
(3) Few shrub seedlings,
(4) Ground cover could be very low if grazed heavily,
(5) Could revert to State I in the absence of proper management.

State IV. Late seral grassland

(1) Perennial grass [*Thyridolepis mitchelliana* (Nees) S.T.Blake, *Enteropogon acicularis* (Lindl.) Lazarides, *Eragrostis eriopoda* Benth., *Eragrostis eriopoda* Benth., *Panicum* spp. and *Digitaria* spp.] dominated grassland,
(2) Annual forbs such as copperburr,
(3) Few shrub seedlings,
(4) Could revert to State III and eventually to State I in the absence of proper management.

Catalogue of transitions

- Transition 1. Mechanical clearing, shrub is removed by either bulldozing or chaining. Two to three years will pass before the paddock is ready for planting crops. Annual forbs and grasses are the common vegetation types and ground cover is dominated by wood debris.
- Transition 2. Unless paddock is raked and readied for planting (transition 3), it is inevitable that State II will revert to State I.
- Transition 3. Removal of wood debris (raking) and planting crop would facilitate the germination of annual forbs and grasses following cropping as well as help recoup some of the costs incurred during clearing.
- Transition 4. In the absence of managed grazing and follow-up shrub control, State III could revert to State I over time.
- Transition 5. Managed grazing and shrub control enables the restoration of perennial grass based grassland.
- Transition 6. The restored grasslands could be cropped with minimum soil disturbance to control shrub establishment. Currently paddocks can be legally cropped three times in 15 years.
- Transition 7. In the absence of grazing management that encourages the maintenance of native perennial grasses, and shrub control, State IV could revert to State I.

One-way transitions from State I culminating in State IV are the desirable ones. Transitions that lead to State I need to be prevented from taking place. Although achieving State IV is the ultimate aim of the restoration process, it will be necessary for transition 6 to take place as required and as permitted by current legislation. However, there is real risk of reversion to State I if appropriate measures are not taken to prevent overgrazing and control emerging shrubs. Paddocks such as shown in Fig. 5*f* could easily be transformed to State I in a relatively short time.

The shrub state (State I) represents a stable state within the Cobar pediplain Social Ecological System of Walker *et al*. (2004) that includes native perennial pastures and woodlands. This state is largely brought about by land-use change in the form of overgrazing and/or the removal of fire from the system (Booth *et al*. 1996*a*) and forms part of a mosaic of landscapes. This state is basically the 'novel' state of Hobbs *et al*. (2009). An alternative stable state (State IV above) was achieved as a result of disturbance in the form of clearing, cropping and grazing management thereby directly altering the shrub population. State IV is equivalent to what Hobbs *et al*. (2009) described as a 'hybrid' state that retains some characteristics of the original system. The resilience of this state is largely dependent on the grazing management system used, and on the control of shrub re-establishment – 'human-managed resilience' in the terms of Walker *et al*. (2004). However, overgrazing could result in another alternative stable state (State III), which is devoid of desirable perennial native grasses, while failure to control shrubs could lead to the re-emergence of State I.

Lewis *et al*. (2009) proposed a transitional model with thresholds for plant biodiversity status and concluded that disturbance-related variables had only secondary influences in determining variation in species composition in grasslands of the Moree Plains under set stocking. Their paddocks, like the State III set-stocked paddocks in our study, exhibited low ground cover and biodiversity. In our study, however, the native perennial grass content was greatly enhanced by light/rotational grazing following the disturbance associated with cropping and it may be that different conclusions regarding the importance of disturbance on the Moree Plains may have been drawn under a different grazing regime.

We conclude that native grasslands do regenerate following cropping after removal of shrubs. In this study the restoration of the major desirable (from a grazing perspective) native perennial grasses did not require seeding as the plants grew naturally, although the generality of this finding requires further investigation. The importance of grazing management, i.e. light/rotational grazing for restoring perennial ground cover following removal of shrubs and temporary cropping has been clearly demonstrated by the study.

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References

Bolger, T. P., and Garden, D. L. (2002). Soil fertility, vegetation dynamics and ecosystem sustainability in Australian temperate grasslands. *In*: 'Soil fertility as an ecosystem concept. Symposium 14, 17th World Congress of Soil Science'. Bangkok, Thailand. p. 1473. (CD-ROM)

Booth, C. A., King, G. W., and Sanchez-Bayo, F. (1996*a*). Establishment of woody weeds in western New South Wales. 1. Seedling emergence and phenology. *The Rangeland Journal* **18**, 58–79. doi:10.1071/RJ9960058

Booth, C. A., Sanchez-Bayo, F., and King, G. W. (1996*b*). Establishment of woody weeds in western New South Wales. 2. Growth and competitive potential. *The Rangeland Journal* **18**, 80–89. doi:10.1071/RJ9960080

Briske, D. D., Fuhlendorf, S. D., and Smeins, F. E. (2005). State-and-transition models, thresholds, and rangeland health. A synthesis of ecological concepts and perspectives. *Rangeland Ecology and Management* **58**, 1–10. doi:10.2111/1551-5028(2005)58<1:SMTARH>2.0.CO;2

Bureau of Meteorology (2010). Rainfall data. Available at: www.bom.gov.au/climate/data/ (accessed 11 February 2011).

Campbell, T., and Hacker, R. (2000). 'The Glove Box Guide to Tactical Grazing Management for the Semi-arid Woodlands.' (NSW Agriculture: Dubbo.)

Chapman, R. (2001). Competition and succession in re-created botanically diverse grassland communities. *In*: 'Competition and Succession in Pastures'. (Eds F. G. Tow and A. Lazenby.) pp. 261–282. (CAB International: Grantham.)

Connell, J. H., and Slatyer, R. O. (1977). Mechanisms of succession in natural communities and their role in community stability and organization. *American Naturalist* **111**, 1119–1144. doi:10.1086/283241

Cunningham, G. M., Mulham, W. E., Milthorpe, P. L., and Leigh, J. H. (1992). 'Plants of Western New South Wales.' (Inkata Press: Sydney.)

Dale, V., Archer, S., Chang, M., and Ojima, D. (2005). Ecological impact and mitigation strategies for rural land management. *Ecological Applications* **15**, 1879–1892. doi:10.1890/03-5330

Daryanto, S., and Eldridge, D. J. (2010). Plant and soil surface responses to a combination of shrub removal and grazing in a shrub-encroached woodland. *Journal of Environmental Management* **91**, 2639–2648. doi:10.1016/j.jenvman.2010.07.038

Date, W. G. (1987). Managing woody weeds with fire in the semi-arid woodlands of NSW. *In*: 'Australian Weeds Conference. Proceedings of the Eighth Australian Weeds Conference'. Sydney, NSW. (Eds D. Lemerle and A. R. Leys.) pp. 59–62. (Weed Society of NSW: Sydney.)

DL&WC (1999). 'Resource Assessment and Monitoring System Data Capture.' Resource Information Unit Publication. (Department of Land and Water Conservation: Dubbo.)

Døckersmith, I. C., Giardina, C. P., and Sanford, R. L. (1999). Persistence of tree related patterns in soil nutrient following slash-and-burn disturbance in the tropics. *Plant and Soil* **209**, 137–157. doi:10.1023/A:1004503023973

Green, D. R. (1989). Rangeland restoration projects in New South Wales. *Australian Rangeland Journal* **11**, 110–116. doi:10.1071/RJ9890110

Grime, J. P. (1979). 'Plant Strategies and Vegetation Processes.' (John Wiley and Sons: London.)

Grime, J. P. (1981). The role of seed dormancy in vegetation dynamics. *Annals of Applied Biology* **98**, 555–558. doi:10.1111/j.1744-7348.1981.tb00792.x

Hacker, R., Toole, I., and Melville, G. (2008). Managing soil fertility for restoration of native grasslands. *In*: 'A climate of change in the rangelands. Australian Rangeland Society, 15th Biennial Conference Proceedings'. Charters Towers. (CD-ROM)

Hams, M. (1992). Implementation of woody weed management in practice. *In*: 'Woody weed management strategy. Proceedings of the National Workshop'. Cobar. pp. 59–61.

Harrington, G. N. (1979). The effect of feral goats and sheep on the shrub population in a semi-arid woodland. *Australian Rangeland Journal* **1**, 334–345. doi:10.1071/RJ9790334

Harrington, G. N. (1991). Effect of soil moisture on shrub seedling survival in a semi-arid grassland. *Ecology* **72**, 1138–1149. doi:10.2307/1940611

Harrington, G. N., and Johns, G. G. (1990). Herbaceous biomass in a Eucalyptus savanna woodland after removing trees and/or shrubs. *Journal of Applied Ecology* **27**, 775–787. doi:10.2307/2404376

Harrington, G. N., Mills, D. M. D., Pressland, A. J., and Hodgkison, K. C. (1984). Semi-arid woodlands. *In*: 'Management of Australia's Rangelands'. (Eds G. N. Harrington, A. D. Wilson and M. D. Young.) pp. 189–207. (CSIRO Publishing: Canberra.)

Hobbs, R. J., Higgs, E., and Harris, J. A. (2009). Novel ecosystems: implications for conservation and restoration. *Trends in Ecology & Evolution* **24**, 599–605. doi:10.1016/j.tree.2009.05.012

Hodgkinson, K., and Freudenberger, D. (1997). Production pulses and flow in rangeland landscapes. *In*: 'Landscape Ecology, Function and Management: Principles from Australia's Rangelands'. (Eds J. Ludwig, D. Tongway, D. Freudenberger, J. Noble and K. Hodgkinson.) pp. 23–34. (CSIRO Publishing: Melbourne.)

Hodgkinson, K. C., and Harrington, G. N. (1985). The case for prescribed burning to control shrubs in eastern semi-arid woodlands. *Australian Rangeland Journal* **7**, 64–74. doi:10.1071/RJ9850064

Hodgkinson, K. C., Harrington, G. N., and Miles, G. E. (1980). Composition, special and temporal variability of the soil seed pool in *Eucalyptus populnea* shrub woodland in central New South Wales. *Australian Journal of Ecology* **5**, 23–29. doi:10.1111/j.1442-9993.1980.tb01228.x

Incitec Pivot (2010). Available at: www.incitecpivot.com.au/nutrient_advantage.cfm (accessed 11 February 2011).

Lewis, T., Clarke, P. J., Whalley, R. D. B., and Reid, N. (2009). What drives plant biodiversity in the clay floodplain grasslands of NSW? *The Rangeland Journal* **31**, 329–351. doi:10.1071/RJ08056

McCrea, A. R., Trueman, I. C., and Fullen, M. A. (2004). Factors relating to soil fertility and species diversity in both semi-natural and created meadows in the West Midlands of England. *European Journal of Soil Science* **55**, 335–348. doi:10.1111/j.1365-2389.2004.00606.x

Millar, G. D., and Badgery, W. B. (2009). Pasture cropping: a new approach to integrate crop and livestock farming systems. *Animal Production Science* **49**, 777–787. doi:10.1071/AN09017

Murphy, S. R., and Lodge, G. M. (2002). Ground cover in temperate native perennial grass pastures. I. A comparison of four estimation methods. *The Rangeland Journal* **24**, 288–300. doi:10.1071/RJ02016

Noble, J. C. (1997). 'The Delicate and Noxious Scrub.' (CSIRO Wildlife and Ecology: Canberra.)

Noble, J. C., and Hodgkinson, K. C. (1992). The woody weed problem in Australian rangelands: assessment, ecology and prospects for management. *In*: 'Woody weed management strategy. Proceedings of the National Workshop'. Cobar. pp. 8–14.

Noble, J. C., and Walker, P. (2006). Integrated shrub management in semi-arid woodlands of eastern Australia: a system based decision support model. *Agricultural Systems* **88**, 332–359. doi:10.1016/j.agsy.2005.06.018

Noble, J. C., Cunningham, G. M., and Mulhan, W. E. (1984). Rehabilitation of degraded land. *In*: 'Management of Australia's Rangelands'. (Eds G. N. Harrington, A. D. Wilson and M. D. Young.) pp. 171–186. (CSIRO Publishing: Canberra.)

Noble, J. C., Harrington, G. N., and Hodgkinson, K. C. (1986). The ecological significance of irregular fire in Australian rangelands. *In*: 'Rangelands: a resource under siege. Proceedings of the 2nd International Rangeland Congress'. Adelaide. (Eds P. J. Joss, P. W. Lynch and O. B. Williams.) pp. 577–580. (Australian Academy of Science: Canberra.)

Noble, J. C., Muller, W. J., MacLeod, N. D., Bodulovic, Z., Jones, P., and Wood, J. T. (2005). Integrated shrub management in semi-arid woodlands of eastern Australia: ground and aerial applications of defoliant to shrubs regenerating after disturbance. *The Rangeland Journal* **27**, 117–134. doi:10.1071/RJ05010

NSW Native Vegetation Act No. 103 (2003). Available at: www.legislation.nsw.gov.au/viewtop/inforce/act+103+2003+fn+0+N (accessed 11 February 2011).

O'Connor, T. G. (1991). Local extinction in perennial grasses. *American Naturalist* **137**, 753–773. doi:10.1086/285192

Pressland, A. J. (1981). Woody weeds in Australian rangelands: is prevention easier than cure? *In*: 'Proceedings of the Sixth Australian Weeds Conference, Volume 1'. (Eds B. J. Wilson and J. T. Swarbrick.) pp. 169–174. (Queensland Weed Society for the Council of Australian Weed Science Societies, City of Gold Coast, Queensland.)

Prober, S. M., Thiele, K. R., Lunt, I. D., and Koen, T. B. (2005). Restoring ecological function in temperate grassy woodlands: manipulating soil nutrients, exotic annuals and native perennial grasses through carbon supplements and spring burns. *Journal of Applied Ecology* **42**, 1073–1085. doi:10.1111/j.1365-2664.2005.01095.x

Rhoades, C. C. (1996). Single-tree influence on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. *Agroforestry Systems* **35**, 71–94. doi:10.1007/BF02345330

Schlesinger, W. H., Raikes, J. A., Hartley, A. E., and Cross, A. F. (1996). On the spatial pattern of soil nutrients in desert ecosystems. *Ecology* **77**, 364–374. doi:10.2307/2265615

Schlesinger, W. H., Reynolds, J. F., Cunningham, G. L., Huenneke, L. F., Jarrell, W. M., Virginia, R. A., and Whitford, W. G. (1990). Biological feedback in global desertification. *Science* **247**, 1043–1048. doi:10.1126/science.247.4946.1043

Silcock, R. G., and Smith, F. T. (1990). Viable seed retention under field conditions by western Queensland pasture species. *Tropical Grasslands* **24**, 65–74.

Tighe, M., Reid, N., Wilson, B., and Briggs, S. V. (2009). Invasive native scrub and soil conditions in semi-arid south-eastern Australia. *Agriculture Ecosystems & Environment* **132**, 212–222. doi:10.1016/j.agee.2009.04.001

Tongway, D. J., and Ludwig, J. A. (1997). The conservation of water and nutrients within landscapes. *In*: 'Landscape Ecology, Function and Management: Principles from Australia's Rangelands'. (Eds J. Ludwig, D. Tongway, D. Freudenberger, J. Noble and K. Hodgkinson.) pp. 13–22. (CSIRO Publishing: Melbourne.)

Walker, B., Holling, C. S., Carpenter, S. R., and Kinzia, A. (2004). Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society* **9(2)**. Available at: www.ecologyandsociety.org/vol9/iss2/art5/ (accessed 6 June 2010).

Westoby, M., Walker, B. H., and Noy-Meir, I. (1989). Opportunistic management for rangelands not at equilibrium. *Journal of Range Management* **42**, 266–274. doi:10.2307/3899492

Wilson, A. D., and MacLeod, N. D. (1991). Overgrazing: present or absent. *Journal of Range Management* **44**, 475–482. doi:10.2307/4002748

Witt, G. B., Harrington, R. A., and Page, M. J. (2009). Is 'vegetation thickening' occurring in Queensland's mulga lands – a 50-year aerial photographic analysis. *Australian Journal of Botany* **57**, 572–582. doi:10.1071/BT08217

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