Threatened Species and Farming

Chariot Wheels

Ecology and conservation in the context of agriculture – Preliminary investigations into population ecology

Author
Paul Foreman
Consultant Botanist
c/o DSE, 8 Nicholson St, East Melbourne, 3001
paulforeman@hotkey.net.au

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Victoria
The Place To Be

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Abbreviations

ARI	Arthur Rylah Institute (for Environmental Research)
DPI	Department of Primary Industries
DSE	Department of Sustainability and Environment
ESAI	Ecologically Sustainable Agriculture Inititative
FRI	Finite Rate of Increase
NC CMA	North Central Catchment Management Authority
PV	Parks Victoria

Table of Contents

Summary

This study was funded by the *Ecologically Sustainable Agriculture Initiative* (ESAI) of DSE and DPI. It is one of seven case studies investigating management techniques for threatened species in the context of improvements in agricultural production that are ecologically sustainable over the long-term.

Chariot Wheels is a small hemicryptophyte of the saltbush family that exhibits summer dormancy to avoid desiccation. It is a nationally threatened species that is now restricted to the south-eastern Riverine Plain and into the western Wimmera. In Victoria it has been recorded from at least 29 predominantly unprotected private land sites. Few specific studies have been undertaken and little of the species life history and reproductive strategy is understood including the impact of grazing.

Three representative sites were selected each from the patho plain west of Echuca (Plains Grassland), the lower Avoca River plain north of Quambatook (Chenopod Grassland) and in the Wimmera west of Watchem (Savannah Woodland) to begin assessing if populations are self-sustaining in the context of agriculture (pastoralism). All three sites supported relatively high quality remnant grassy habitat, that has never been cultivated and only lightly grazed by stock. Basic demographic data was collected by permanently marking a selection of plants, and the physical context was described by collecting habitat and management data. Recruitment, fecundity and mortality (used to calculate population growth rates or the Finite Rate of Increase - FRI) required data from a full 12 month cycle and was compiled from four field visits in September and December 2003 and February and July 2004. Physical description consisted of vegetation and soil observations (undertaken mainly in Sept 2003) plus details of grazing throughout the year based on interviews with each land manager.

The annual life cycle observed began with either resprouting or germination in late autumn or winter (immediately following the year's first significant rainfall), followed by rapid vegetative growth, budding and flowering in the spring months, seed maturation, shedding and dispersal via wind or ants in the early summer and finally dying back into dormancy by late summer and autumn. Fecundity (seed production?) was linked to plant size and was spatially patchy within sites. Between sites fecundity was highly variable with greater seed production per plant linked more to habitat condition and population size and isolation than to grazing pressure. Preliminary longevity data (correlating tuber ring-banding with stem height) suggested plants may take up to 5 years following germination before making any significant contribution to population fecundity and plants may not live much beyond about 10 years.

At all but one site, the FRI was significantly below 1.0 as the high mortality of adult plants due to the unusually dry summer (January to April 2004) was not off-set by recruitment which was uncommon and patchy. In fact, germination was essentially not observed at the two grassland sites. Germination at the Wimmera site was extremely patchy and was apparently linked to microflooding created by the complex gilgai microrelief. It is speculated that microflooding is required to both minimise competition and break chemical induced seed dormancy.

If the demographic trends observed in 2003/04 continue, at least the two grassland populations are likely to quickly decline. However, given the unusually dry conditions during the study period (especially the very dry summer), it is not possible to make any confident predictions about future trends without further monitoring and experimentation.

It is speculated that the probability of episodic recruitment is related to microhabitat heterogeneity and the interaction with climate. The two grassland sites appear to have a relatively homogeneous patterning of microhabitats that may even have been created by past over grazing and may reduce the probability of recruitment. It is concerning to note that if this hypothesis is correct in a climate change scenario, the fate of many populations may be beyond direct management control.

Despite the low stocking levels observed (rotational systems, <1 DSE/ha/year) and the fact that plants with drought avoiding life histories and at or below-ground meristems are very resilient and persistent, grazing can still have an impact on population ecology. Stocking level for instance was positively correlated with adult plant mortality. Grazing appeared to exaggerate the 'normal' level of mortality suggesting plants were vulnerable to trampling during the dormancy phase. Adult plant size, fecundity, form and health as well as germination and recruitment and FRI were all apparently independent of grazing. However, the first four of these were probably not affected in 2003/04 because stock where excluded at all 3 sites from mid-winter to early summer. Germination and recruitment was likewise not affected primarily because it was too uncommon and patchy to assess.

Consistent with the typically episodic recruitment of such perennial grassland forbs, it is possible grazing may influence germination and recruitment rates in more climatically favourable years. As FRI is primarily driven by recruitment, the link between grazing and mortality had little influence on reproductive success.

Without further data these results can only at best be considered preliminary. An expansion of the project by introducing 'treatments' such as grazing exclosures, further replication, more time and multivariate analyses will serve to clarify linkages and relationships. The multivariate analyses are required to ensure the impact of factors such as population size and isolation, genetic structure, geographic location and habitat type and condition are considered. Only these additional investigations will help determine meaningful grazing tolerance limits.

Other aspects that warrant future study include: the process of seed germination (using both *in situ* and *ex situ* experiments), the role of the soil seed bank (including the role of ants in dispersal), the effect of competition (indigenous and exotic plants), the role of heterogeneous soil microrelief and the interaction with climate, and the impact of inbreeding depression (link between genetic structure and fecundity).

The level of historical habitat destruction has overwhelmingly contributed to the species current threatened status. Conservation requires both the prevention of further loss and the restoration of degraded sites. It is likely further thorough searching for extant populations in areas of suitable habitat within the natural range, establishing additional demographic monitoring points and securing populations using appropriate mechanisms would make a tangible contribution to species recovery.

Management suggestions include maintaining *status quo* grazing regimes until more is known.

1 Introduction

Ecologically Sustainable Agriculture Initiative (ESAI)

"Threatened Species and Farming" is a sub-project of the ESAI. This project will identify how agricultural practices might be modified to help conserve selected threatened species as part of working toward ecological sustainability. The project will document case studies of selected threatened species in four bioregions: the Victorian Riverina, Wimmera, Victorian Volcanic Plain and Gippsland Plain. The farms considered include examples from the meat, wool, dairy and grain industries. This case study focuses on Chariot Wheels *Maireana cheelii* (R. Anderson) Paul G. Wilson of the Saltbush family (Chenopodiaceae).

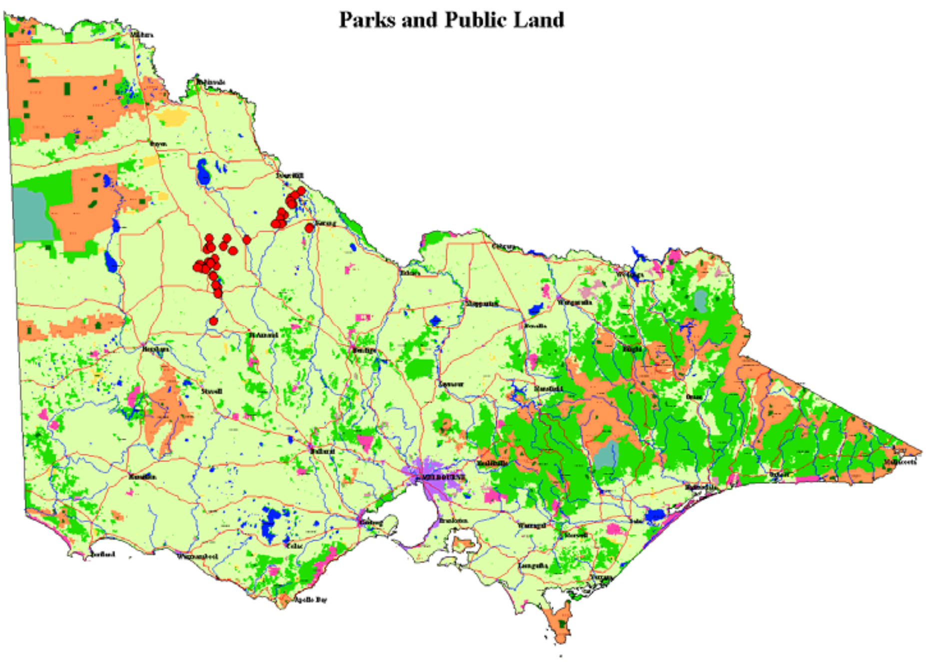
Chariot Wheels description and distribution

Chariot Wheels is a tufted perennial forb with prostrate to erect, slender and woolly branches to 20 cm long arising from a swollen taproot (Walsh and Entwisle 1996). It is a seasonal, herbaceous hemicryptophyte with buds just below soil level that largely dies back (or persists in a semi-deciduous state) into a dormancy during the harsher summer months to avoid desiccation. Plants typically re-sprout each year during late autumn and winter following the first significant rainfall.

Whilst Chariot Wheels has been recorded from Victoria to Queensland, today it is likely restricted to the south-eastern Australian Riverine Plain of Victoria and NSW with some extension into the Victorian Wimmera. It is likely extinct in Queensland were it was last recorded in 1936 (Mavromihalis 2004). In Victoria, Chariot Wheels extends from Donald and Birchip on the eastern margin of the Wimmera, to the Avoca and Loddon River flood plains west and north of Kerang, and across to the patho plains west of Echuca. A total of 29 populations are recorded in the Flora Information System (FIS) dating back to 1975 (Pers. Obs.; Harden 1990; Walsh and Entwisle 1996; Foreman and Bailey 1996; Foreman and Garner 1996; Orr and Diez 1999; O'Brien and Diez 2001; DNRE 2001; DNRE 2002) (See Figure 1). Anecdotal evidence suggests there are likely more populations, especially in the Wimmera and the patho plains.

Figure 1: Distribution of Chariot Wheels in Victoria

Source: FIS. Records denoted by red dots; Public Land is shaded light-green and Conservation Reserves (including National Parks) are highlighted in dark-green, orange, olive-green, pink and red. Note: recent survey work on the patho plains is not included.

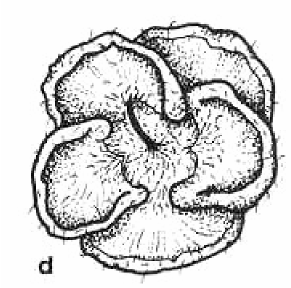


Chariot Wheels occurs on bleached (grey), non-friable, heavy clay scalds or depressions usually subject to seasonal saturation due to localized runoff and high soil compaction. Such areas are typically very sparsely vegetated with a high proportion of bare ground (incl. some cryptogams) often created by wind erosion and/or over-grazing during past droughts. The majority of sites are located on freehold land and roadsides that have never been cropped and only ever subject to stock grazing (sometimes very intensive, but episodic) and tend to support relatively rich remnant grassland or open grassy woodland vegetation with a low weed cover. Annual rainfall ranges between 325 and 400 mm with the average about 350 mm.

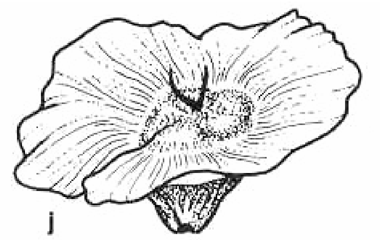
Chariot Wheels is most similar to four bluebushes in terms of lifeform, geographic distribution and habitat preference: Wingless Bluebush (*Maireana enchylaenoides*), Dwarf Bluebush (*M. humillima*), Bottle bluebush (*M. excavata*) and Hairy Bluebush (*M. pentagona*) all readily distinguishable on fruiting perianth morphology (Figure 2). All four species are largely found in Victoria's northwest and are similarly herbaceous hemicryptophytes with a swollen taproot. Habitat differentiation appears to be primarily driven by microhabitat preference, especially along a soil type sequence of increasing texture, possibly linked to reproductive strategy.

Figure 2: Fruiting perianths of related Bluebushes
Source: Flora of Victoria (Walsh and Entwistle 1996)

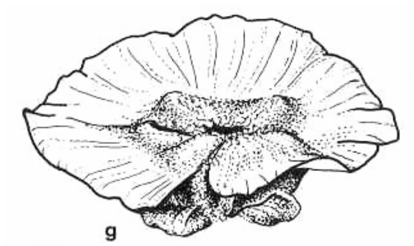
Maireana enchylaenoides



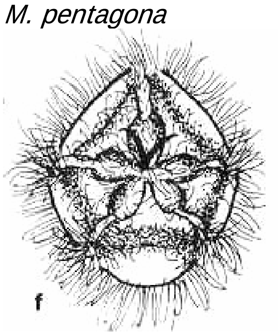
M. humillima



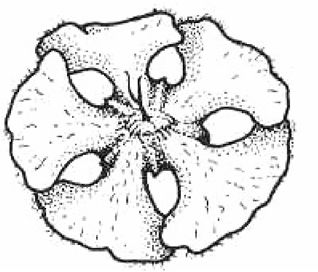
M. excavata



M. pentagona



M. cheelii



A study of species-rich grassland vegetation at Terrick Terrick National Park north of Bendigo (Foreman 1996; Parks Victoria 2004) showed that a close relative of Chariot Wheels (Bottle Bluebush) was readily eliminated by cultivation. This study also showed such Bluebushes persisted well under conservative stock grazing and that it is likely ongoing disturbance is required to maintain reproductive opportunities, especially in the context of weeds.

Chariot Wheels is listed as Vulnerable under the Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth) and Vulnerable in Victoria (Flora and Fauna Guarantee Act 1988) and NSW (Threatened Species Conservation Act 1995). The status of Vulnerable indicates that the species is not immediately in danger of extinction in the wild but could soon become so if the known populations are not secured. A National Recovery Plan is currently in preparation (Mavromihalis 2004).

Chariot Wheels life history and reproductive ecology

Hemicryptophytes, perennial herbaceous forbs that avoid the harsher summer months by dying back into a dormancy phase as a woody subterranean tuber, are common amongst the grassland flora of the semi-arid south-eastern Australian Riverine Plain. Plants only emerge from dormancy, to produce fresh growth, flower and set seed, during the more favourable winter and spring periods when most rainfall is received and temperatures are cool to mild.

In the case of Chariot Wheels, fresh new branches resprout following the first significant autumn or winter rains. Resprouting either occurs at ground level or aerially if the previous year's stems have persisted over summer. Typically the resprouts will almost immediately begin producing single (bisexual) flower buds in leaf axils. Flowering quickly follows with the emergence of five anthers and two stigmas and typically reaches a peak in late winter or early spring depending on the season. No nectar is produced so pollination is probably facilitated by wind and given the prolific level of seed production by most populations it is assumed the flowers are self-compatible. The end of the flowering phase is marked by the loss of anthers and the emergence of a fruiting perianth with five radial wings and a cottony indumentum. Seed maturation occurs when the perianth obtains a diameter of 5 to 6 mm and drys out to a pale beige colour with a brittle, papery texture that is readily dislodged from the stem. Seed production typically reaches a peak in early December with the first hot weather of the summer when the seeds either fall to the ground, are scattered by wind or removed by ants. It is unclear what proportion of the annual seed crop is predated by ants, how they are used, how far they are transported and what role this process plays in the plant's reproductive biology, if any. It is also unclear if and how any seeds end up in the soil as a seed bank, how long they persist and what role this process plays in reproductive biology. Most plants have shed their seed by mid summer when they have already begun dying back into the dormant phase ready for re-emergence in the following winter.

There is little published or unpublished information on the reproductive biology of Chariot Wheels and for the Bluebushes in general. One controlled glasshouse experiement, looking at the germination and growth response of eight common and rare Bluebush species from the Victorian Riverina (Dimech *et al.* 2001), suggests that Chariot Wheels seeds may have some kind of germination dormancy such as a water soluble inhibitor in the perianth that is only removed by prolonged soaking. This is consistent with observations in the field. Chariot Wheels is almost exclusively found in microhabitats that are subject to seasonal microflooding or saturation such as natural clay depressions and scalds. It is presumed that germination can seasonally occur in these depressions following suitable late autumn or early winter rains after which the remaining seeds readily imbibe water and germinate on or close to the sodic mud surface once the water has been absorbed or evaporated away. The structure of the depressions is likely crucial for creating microflooding events of a suitable duration. Too short a period would be insufficient to break dormancy and too long libel to drown the embryo or encourage hostile wetland vegetation. Recruitment will only be possible if germinants can develop a large enough tuber during spring to persist over the following summer.

Chariot Wheels population ecology

Understanding plant population ecology is fundamental to the recovery of any threatened species. At its simplest, plant popu計uation ecology is about understanding the factors that control changes in population numbers over time by monitoring trends in births, deaths, immigration and emigration. In order to determine how we might act to facilitate recovery and prevent species extinction we need to know: are the populations stable, increasing or declining and why? (Gibson 2002). The stated objective of the Recovery Plan is to "increase the probability of important populations becoming self-sustaining in the long-term" (Mavromihalis 2004).

Although some Chariot Wheels populations have been monitored under DSE's VROTpop program, little data is available on population demography. Germination has been observed in the field, but no data has been collected on recruitment or mortality rates. We can only draw inferences about population ecology from indirect sources such as historical records, distribution patterns, habitat type and management systems.

As is typical for threatened species in agricultural landscapes, Chariot Wheels is likely rare and threatened today because of habitat loss. Over 95% of the Riverina and Wimmera Bioregions have been cleared for primary production and some habitat types have been almost entirely wiped out. The grassy habitats that support Chariot Wheels in the Riverina and Wimmera have been massively depleted by between 92% and 97% (DSE 2004).

As the vast majority of the known populations are on freehold land, Chariot Wheels remains vulnerable to not only on-going land clearing and habitat loss associated with degrading processes such as weed invasion, but also to factors that control demography within populations. It is currently assumed that the management regimes present at most remnant populations are broadly compatible with Chariot Wheels conservation, but this is likely to be highly variable with some sites self sustaining and others clearly in trouble.

Study aims

The primary aim of this study is to determine if populations are self-sustaining, and if so, describe the management regimes present in order to define the limits of compatibility with agriculture. However, it is critical to note that agricultural practices will not be the only factor influencing population performance. In fact, it maybe that other factors such as climate and habitat area are far more important for long term persistence. In the context of the limited duration and scale of the ESAI project, this study will only begin to answer these questions Consequently, recommendations for future study are presented.

2 Methods

Site selection and description

Three sites were selected to collect basic data on plant population ecology. These were chosen to represent a range of habitat types throughout the natural geographic range of Chariot Wheels in Victoria (Figure 1). Consistent with the objective of the ESAI project, all sites are part of an active commercial farm and subject to domestic stock grazing. Consideration was also paid to population size and isolation, property area and location, and the condition of habitat as measured by species richness and degree of weed cover.

Data collection

Three replicate 1 m^2 (1 by 1 m) permanent quadrats (9 in total) were sited to capture the range of microhabitats in which the plant occurred at each site. Different coloured tags (Red, Blue and Black) were used to readily differentiate between the three replicates both in the field and during data analysis. Each was positioned such that approx 50 plants would be marked.

All plants within these quadrats were marking using two techniques: (1) hardened steel, 10 cm “orchid pins” each with a 20 mm diameter anodized aluminium tag stamped with a unique number (1 to 200), and (2) a grided aluminium frame with 25, 400 cm^2 (20 by 20 cm) unique coordinate regions (A1 to E5). All sites were visited 4 times during the project: September 2003, December 2003, February 2004 and July 2004 – representing one full annual cycle and assessed for a range of attributes:

- **Plant category (in the Field):** Each plant was categorised into 1 of 6 life stage categories. Germinant (SL – cotyledons present), Resprout (R – ground or aerially), Adult Non-flowering (ANF), Adult Flowering (AF), Dead (D) and Alive Undefined (AU).
- **Fecundity:** The number of flower buds, flowers and/or attached seeds.
- **Height (cm):** The maximum branch or stem length, irrespective of form (Note: any plant < 0.5 cm in height was placed in the Resprout category).
- **Stem Number:** The number of stems evident at ground level.
- **Browsing:** The number of stems evidently browsed by animals or insects or has otherwise died back or been removed (Note: 0 indicates no browsing).
- **Health:** Each plant was subjectively categorised into 1 of 3 categories. Vigourous (V – 0% disease or branch/leaf loss), Fair (F – to 50% disease or branch/leaf loss) or Poor (P - >50% disease or branch/leaf loss) health as indicated by proportion of leaf senescence, disease or lack of growth.
- **Form:** Each plant was subjectively categorised into 1 of 3 categories. Erect (E), Decumbent (D) and Prostrate (P).

Final life stage categorisation for the 2003/04 season was undertaken at the end of the summer/autumn dormancy period after the July 2004 assessment. Note that Fecundity, Height, Stem Number and Browsing was given as the highest number obtained during the season.

In addition, seed and germinant densities were measured for all quadrats during each of the four assessments. These data were expressed as the number of detached seeds and germinants in each of the 25, 400 cm^2 coordinate regions. To track the germination survivorship each germinant was temporarily marked with a tagless “orchid pin” that was removed during subsequent visits if they died. Those that survived until the July 2004 assessment were then permanently marked and denoted as 2003/04 recruits for subsequent assessment beyond the life of this project (ie. under the Recovery Plan implementation).

Data were collected on the general nature and condition of the vegetation throughout the three paddocks and immediately surrounding the quadrat locations. Long-term monthly rainfall data from a range of the closest permanent weather stations were obtained from the Bureau of Meterology in Melbourne. Population area was estimated by rapid visual assessment, paddock size was measured from 1:100,000 and 1:50,000 topographical maps, and population size was estimated using density by area data or obtained from the Recovery Plan (Mavromihalis 2004).

To aid site description (close to quadrat locations) and to help illustrate the relative position of Chariot Wheels in site microrelief and in comparison to other Bluebushes, a series of three 20 m long microrelief transects were established using a nylon string tied to wooden stakes and a light-weight spirit level. Elevations were then measured at metre intervals along the transect to the nearest half centimeter from below the string level to the ground surface using a retractable aluminium builders tape. At each interval, the presence or absence of any Bluebush species (plus selected *Sclerolaena* species – also in Chenopodiaceae) was recorded with a 1 m diameter visually assessed sub-quadrat.

The vegetation present at each quadrat was described using data collected on vegetation structure (percentage cover to the nearest 5% for bare ground, bryophytes and lichens, organic litter, rocks and stones, water, weeds and indigenous plants) and floristics (percentage cover to the nearest 5% for all vascular flora species).

To help describe the differences between microhabitats, the soil surface and sub-soil to 20 cm was described at all quadrats, plus five additional quadrats (two at Pine Grove and Budgerum, and one at Warnup) using the following variables: field texture and colour, pH, surface condition and dispersion behaviour. Field texture and surface condition categories follow McDonald (1984), colour categories were determined using a Munsell Color Chart, pH was measured using a horticultural test kit (Manutec) and the dispersion was gauged using the Emerson Aggregate Test (Charman and Murphy 1991).

Data was also collected to define longevity. It was presumed the woody tubers would contain growth rings of some form and given the plant's dramatic seasonal growth behaviour, not only would they be highly visible in transection, but they could be directly used to estimate age. Correlations between growth ring data and above ground attributes such as maximum branch length and numbers of stems could be used to estimate the age of plants without digging up tubers. To test this relationship, 6 plants of various sizes were sampled from the three sites and various attributes measured: tuber length, tuber diameter, stem height, stem number and stem basal area. Tuber rings were counted by examining tuber transections under a monocular microscope. Each transection was prepared on a glass slide and stained with congo red vegetable stain.

Data analysis

The dynamic nature of the population was partially analysed using a life cycle diagram (see Gibson 2002).

Annual or Finite Rate of Increase (FRI), the ratio of the number of plants per unit area at time t+1 to the number in the previous year t (N_{t+1}/N_t), was calculated using the following equation (from Gibson 2002):

$N_{t+1} = N_t + B – D + I – E$ (Equation 1)

Where: B is the number of births (recruitment or survival of germinants)
D is the number of deaths (mortality)
I is the number of immigrants
E is the number of emigrants

In the case of perennials like Chariot wheels, births are synomyous with recruits: those individuals that survive beyond germination and make a successful transition into adulthood at approx 1 year of age. Number of deaths is the mortality rate of adults and does not include unsuccessful germinants. As Chariot Wheels does not regenerate vegetatively nor experiences dormancy longer than a single summer season, it is assumed that there is no population immigration or emigration – these attributes would only apply to the seed life stage in transition matrix models (Gibson 2002).

No cluster analysis was undertaken on the floristic data from the 14, 1m^2 quadrats. Although these reflect the complex microhabitat diversity within these grassy remnants, at the landscape scale this variation is considered typical of the heterogenous nature of remnant grassy vegetation in the Riverina and Wimmera.

No analysis of variance (ANOVA) was undertaken due to a lack of replication.

3 Results

Site locations and general description

Three sites were selected. For confidentiality each are defined throughout the report by location names only: (1) Pine Grove - a private grassland reserve in the Riverina north of Pine Grove and ~28 km west of Echuca; (2) Warnum - a private property east of Warnum in the Wimmera ~4 km north-west of Watchem (south of Birchip); and (3) Budgerum – a private property also in the Riverina south of Budgerum (close to the Avoca River) ~9 km north-north-west of Quambatook.

Pine Grove represents the eastern edge of the plant's geographic range, Warnup the western extreme and Budgerum is roughly in the middle on the lower Avoca River floodplains close to the Murray River (Figure 1).

Pine Grove was purchased by Trust For Nature in 2000 to conserve Riverine grassland biodiversity. (Trust for Nature was formerly the Victorian Conservation Trust: a not-for-profit statutory authority established in 1972 to facilitate private land nature conservation.) Most of the 168 ha property has never been cropped and supports Plains Grassland (EVC 132, Endangered) vegetation that is habitat for a range of threatened species including Plains-wanderer (*Pedionomus torquatus*) and Red Swainson-pea (*Swainsona plagiotropis*) (Pers. Obs.). Despite the size of the property, the plants are apparently restricted to a handful of patches of suitable habitat (perhaps covering as little as 1 ha) on the margins of a large ephemeral wetland (Lignum Swampy Wetland, EVC 823, Depleted). The total population was estimated to be 10,000–50,000 in 2003 (Mavromihalis 2004).

Warnup is visually dominated by a scattering of Black Box (*Eucalyptus largiflorens*) and some Buloke (*Allocasuarina luehmannii*) typical of remnants in the Wimmera Bioregion. The 36 ha remnant has never been cleared or cropped and supports a relatively high quality example of Plains Savannah (EVC 826, Endangered) that is habitat for a range of threatened flora including Long Eryngium (*Eryngium paludosum*) and Rohrlarch's Bluebush (*Maireana rohlarchii*) (Foreman and Bailey 1996). The total population was estimated to be 10,000–50,000 in 2003 (Mavromihalis 2004) and is scattered in dozens of largely discrete patches of suitable habitat (perhaps covering up to 5 ha) mainly in the eastern half of the paddock adjacent to Cronin's Tank Road.

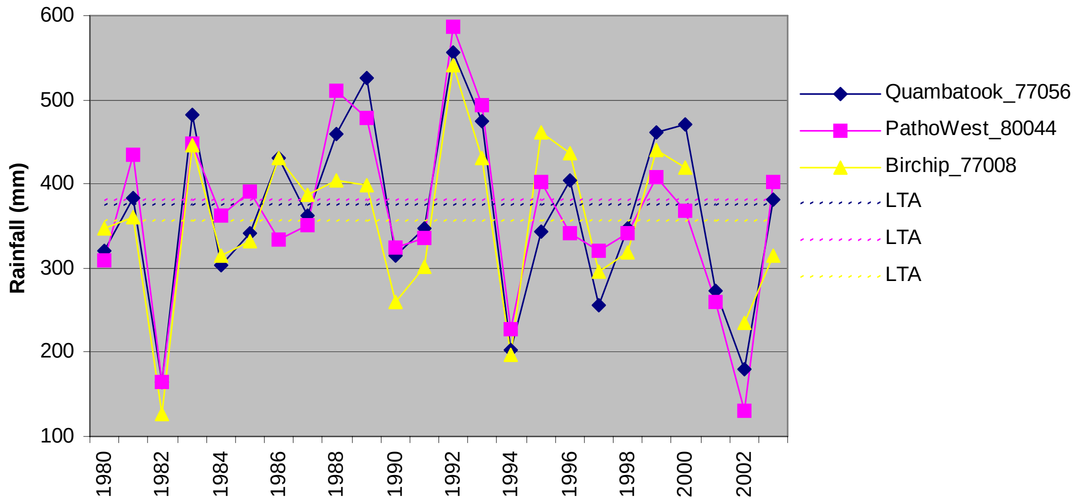
The Budgerum property consists of a mix of grassland and grassy woodland habitat, the former being a form of Chenopod Grassland (EVC 829, Endangered) and the later a Riverine Chenopod Woodland (EVC 103, Vulnerable) dominated by Black Box. It is likely the Chenopod Grassland is a disclimax form of a former chenopod grassy shrubland that has been modified by stock grazing. The 120 ha paddock, adjoining the Avoca River, has never been cultivated and supports relatively high quality vegetation that is habitat for a range of threatened flora including Leafless Bluebush (*Mairerana aphylla*) and Veined Pepper-cress (*Lepidium phlebopetalum*) (Foreman and Garner 1996). Scattered widely over an area of ~20 ha, mainly in the south, the population was conservatively estimated to be 50,000-200,000 in 2003 (Mavromihalis 2004).

Rainfall

Average annual rainfall at Pine Grove, Warnup and Budgerum is 381.0, 356.5 and 374.8 mm respectively. These data were obtained from nearby permanent weather stations maintained by the Bureau of Meteorology: Patho West (80044), Birchip (77008) and Quambatook (77056) respectively. Whilst rainfall patterns are highly variable there is some indication of lower rainfall in the recent times, with two of the three most severe droughts since 1980 occuring in the last decade (1994 and 2002) (Figure 3).

Figure 3: Average annual rainfall from 1980 to 2003 for the three permanent weather stations

Patho West (80044), Birchip (77008) and Quambatook (77056). LTA = Long-term Average

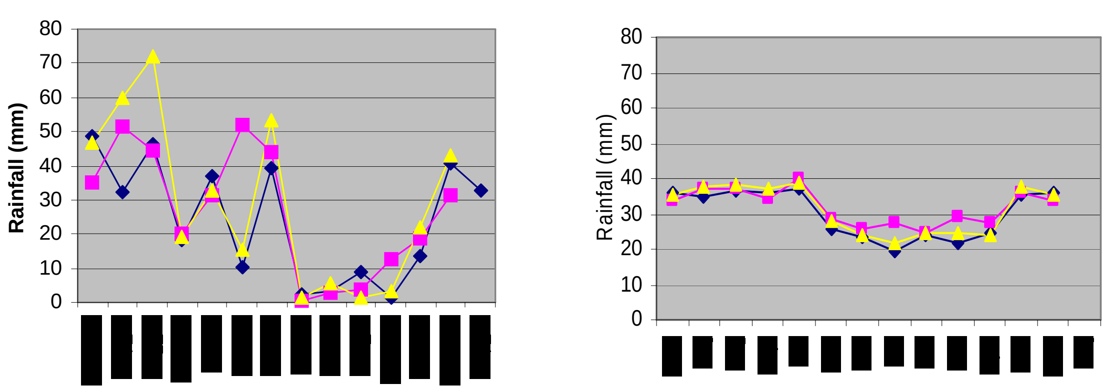


Closer examination of monthly rainfall (actual and long-term average) patterns during the study period shows firstly that most rain falls between May and Oct when Chariot Wheels is germinating, actively growing, budding and flowering. Secondly, roughly the same levels and patterns of rainfall is received at each site, although there is significant variation in actual monthly falls that reflect the general patchiness of rainfall patterns. And thirdly, the summer of 2003/04 was particularly dry with next to no rainfall recorded at any site from January to April 2004 (Figures 3 and 4). This is the second lowest rainfall recorded for this four-month period since records began in 1890 at the Birchip station. Only in 1923, 1912 and 1967 was either less rain or equivalent rainfall conditions recorded over these months. Statistically the extreme 2003/04 dry summer was roughly a one-in-thirty-year event (Bureau of Meteorology).

Figure 4: (A) Rainfall from June 2003 to July 2004 and (B) Long term average monthly rainfall each for the three permanent weather stations

Pink squares - Patho West (80044), Blue diamonds - Birchip (77008) and Yellow triangles - Quambatook (77056)

(A) (B)



Site management context and history

Although a conservation reserve, Pine Grove is grazed by sheep to control biomass and weeds. The property was formerly owned by a dairy farmer from Lockington and was rotationally grazed by dry cows during the winter months for many decades (Pers. Obs.). Today the grazier manages the reserve in conjunction with a nearby property for wool and mutton production. The paddock was subject to two grazing episodes during the study period: (1) from May to July

2003, and (2) from June to August 2004. The first episode involved 200 1-year-old mixed merino lambs (35-40 kg each), whilst the second period of grazing involved a mixture of 160 ewes (~50 kg each) and 200 1-year-old mixed merino lambs. Some minor supplementary feeding using pellets occurred in 2003 (Table 1).

Warnup is also grazed with sheep for wool and mutton production. The remnant habitat in which Chariot Wheels occurs, occupies the corner of a larger 196 ha paddock the balance of which is regularly cropped. Merino lambs are typically purchased in October and graze the entire paddock (remnant habitat and stubble) over the summer months before they are sold as 45-50 kg wethers in autumn. The paddock was subject to one grazing episode during the study period: 500 head from January to May 2004. Previously a mob was in the paddock from December 2002 to February 2003. Stock were supplementary fed oats for the first time in the paddock during 2004 due to very poor rainfall (Table 1; Figure 4).

Budgerum is also grazed with sheep for wool and mutton production. The 140 ha paddock is typically grazed in the autumn when the native pasture provides better grazing than comparable exotic pastures. Hay is used for supplementary feed in most years. The paddock was subject to one grazing episode during the study period: 140 lactating Merino ewes (with 100% young lambs) in July 2004 (Table 1).

Indicative stockings levels, based on manager interviews, showed the average grazing level over the study period in DSE/ha/yr ranged from 0.10 to 0.72 at Budgerum and Warnup respectively. In each case the regime was effectively rotational, with the paddocks rested for extended periods (over 90% of the study period in the case of Budgerum). The grazing episodes occurred in summer and autumn (Warnup) or during winter at levels up to ~2.5 DSE/ha/month (Table 1). The regime at Warnup is more dictated by paddock configuration and water constraints as stock cannot use the grassy woodland section if there is a crop in part of the balance of the paddock (as in most years). The timing of grazing at the two grassland sites is not constrained by such issues and is more dictated by the condition of the pasture (ie. cover) and the needs of the stock throughout the year. In the case of Pine Grove at least some consideration is also paid to the growth cycle of the different pasture elements. For instance, the composition of the pasture can be manipulated by timing grazing to coincide with the autumn break when exotic annual grasses are germinating and at their most vulnerable.

Table 1: Comparative stocking levels during study period

Note: DSE/ha/yr figures are indicative only and likely over estimates as adjustments have not been made for supplementary feeding which occurred at all sites to some degree. * = DSE/ha/yr figures adjusted down at Warnup as stock were purchased as lambs and adjusted up at Budgerum as ewes (100%) had lambs.

Site	Stock Type	2003						2004							Mon	Area	DSE/ ha/yr
		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Ave	(ha)	
Pine Grove	Mixed ewes and lambs	200	0	0	0	0	0	0	0	0	0	0	360	360	70.8	168	0.39
Warnup	Merino lambs and whethers	0	0	0	0	0	0	500	500	500	500	500	0	0	192.3	196	*0.72
Budgerum	Merino ewes with 100% lambs	0	0	0	0	0	0	0	0	0	0	0	0	140	10.8	120	*0.10

Quadrat locations and descriptions (including soils, veg structure and florsitics)

The populations selected at each site were sampled using three replicates (9 quadrats in total: 3 of Blue, Black and Red) in a representative part of the site that reflected the range of microhabitats present. These microhabitats included grey, pale-red or red scalds, natural hardsetting depressions and gilgai-complex shelves. In order to sample widespread and immediately adjacent microhabitats that did not contain Chariot Wheels, five additional quadrats were established to sample/contrast soil and vegetation characteristics. These microhabitats included red rises, deep gilgai depressions and grey puffs (the later two with friable, deeply cracking soils) (Appendix 1).

Structurally the vegetation in the 9 primary quadrats was an open grassland or herbland some distance from trees or shrubs. Generally there was a high cover of bare ground (30 to 90%), a low cover of soil crusts or cryptogams (lichens, mosses, liverworts or algae - <5-10%), a low cover of litter (<1-5%) and no rocks. The cover of weeds (mainly annual forbs and grasses such as Medic **Medicago* spp. and Annual Rye-grass **Lolium rigidum*) was highly variable with some sites effectively weed-free (<1%) while others were visually dominated by weeds (up to 50%). One quadrat at Warnup (ie. Blue) was severely infested with the perennial exotic Bulbous Meadow-grass **Poa bulbosa* – a significant invasive weed in the Wimmera. With one exception (ie. Budgerum – Red), all sites had a very high cover of indigenous species, dominated by Chariot Wheels. The Budgerum site had a particularly high cover of the annual forb, Golden Sunray *Hylosperma glutinosum*, which was particularly abundant throughout this site (Appendix 2).

Although no water was directly observed at any of the quadrats during any of the four visits, the microrelief clearly showed that most sites were likely to be temporarily flooded from time to time. There was clear evidence that such microflooding had occurred at Warnup in 2003 prior to September for instance (Pers. Obs.).

Whilst the additional quadrats were all grasslands or herblands, they tended to have a higher cover of exotic plants and a lower cover of indigenous species, presumably due to the more friable nature of the soil – which is more naturally dynamic and more readily exploited by exotics (Appendix 2).

The richness data provide a less instructive reflection of the difference between the quadrats, especially the primary quadrats compared with the five additionals. Indigenous richness for instance varied greatly (from 3 to 17 species) across all 14 sites, with only marginally more exotic species recorded in the additional quadrats (Appendix 2).

Soil cores down to 25 cm (in 2 to 5 sections) showed that all sites exhibited considerable micro-complexity in soil texture and colour, as well as surface characteristics such as dispersion properties and the nature of cracking. Although the soils at each quadrat were all heavily textured grey to red clays throughout most of their depth, the surface texture was quite variable resulting in uniform, gradational or duplex soils. In general the microhabitats that supported Chariot Wheels were more uniform in texture - of a paler colour and of a heavier texture at the surface (light to medium clay), usually subject to some slaking indicating the presence of sodicity and a vulnerability to wind erosion. Whilst some of these microhabitats were capable of significant cracking, most were hard setting, taking on concrete-like characteristics when dry (Appendix 3).

At least at Pine Grove and Budgerum the soils of the scalds on which Chariot Wheels occurs today are identical to the those of the adjacent red rises, except for the apparent absence of a light clay or sandy clay loam surface or A-horizon and different surface characteristics. This suggests these scalds may have been created or expanded in relatively recent times perhaps by post-settlement management practices (ie. overgrazing during drought) (Appendix 3). The implication of this observation is that Warnup has not been as significantly modified (or degraded) by agricultural practices.

Another obvious difference between Warnup and the two grassland sites is the presence of a better developed “crabhole” or gilgai microrelief consisting of three primary structural components: depressions, shelves and puffs – broadly representing a continuum from the lowest points in the landscape were water pools most frequently to the highest points where flooding is least frequent. Each exhibit very different physical soil characteristics and result in a microrelief that can range in metres over very short distances (Note: transects in this study only show a proportion of this variation). This complex patterning represents significant microhabitat heterogeneity with Chariot Wheels tending to occupy particular types of depressions and shelves. The gilgai microrelief at Pine Grove and Budgerum is significantly less developed.

Microrelief transects

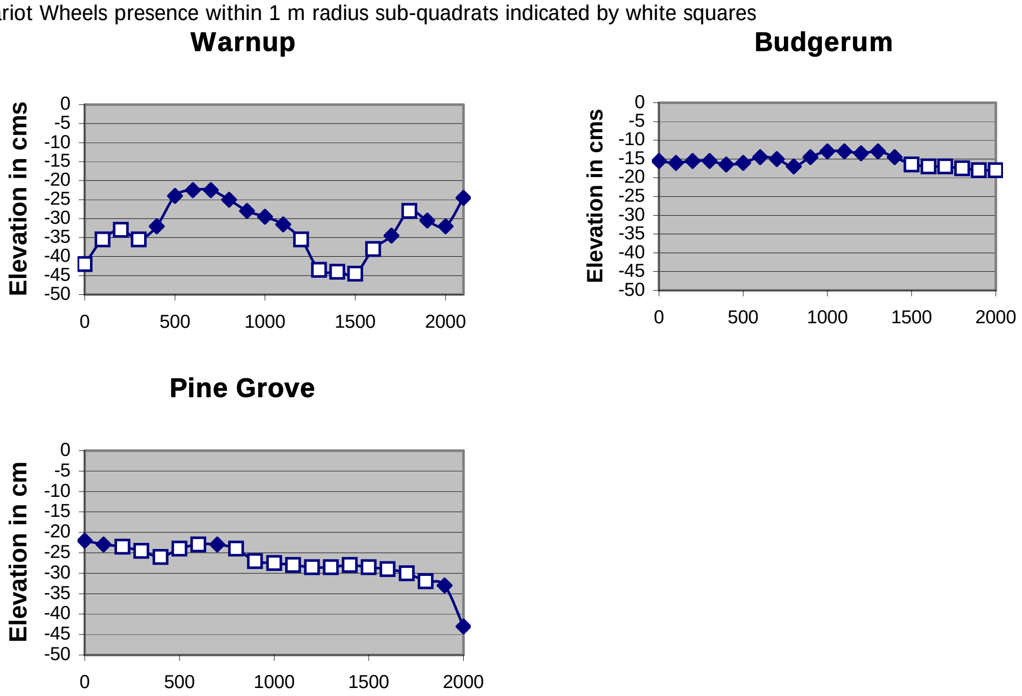
The microrelief transects undertaken at each site within the immediate proximity of quadrats were positioned to represent the variation in microhabitats. Whilst the variation was subtle (from 5 to 22 cm in range over 20 m), the transects show how the patchiness of the plant's distribution is linked to microrelief. In general Chariot Wheels tended to occupy the lowest and flattest parts of the transect landscape except where it dropped into a cracking gilgai depression (eg. at Pine Grove) (Figure 5; Appendix 5). The preferred habitat generally coincided with pale-coloured, heavily textured soils with a very flat surface exhibiting the hardsetting and dispersive characteristics previously described.

Although Chariot Wheels did share part of its microhabitat with the generalists *Maireana excavata* and *M. pentagona*, it tended to dominate, particularly in the scalds and depressions. A range of other chenopods replaced Chariot Wheels at the higher points in the microrelief (eg. *Sclerolaena diacantha*, *Maireana humillima* and *M. rohrlachii*), depending on the site's soil and vegetation type (Appendix 5).

Comparing sites, Warnup exhibited significantly more microrelief variation and complexity than the two grassland sites and it was at this site that Chariot Wheels occupied a far greater range in micro-elevation (ie. 16 cm range cf. 9 and 3 cm at Pine Grove and Budgerum respectively) (Figure 5). Although not clear in the microrelief transects, the spatial patterning of Chariot Wheels was much more patchy at Warnup, with the population clearly segmented into numerous discrete patches corresponding to the complex spatial patterns of the gilgai microrelief. The populations at both grassland sites were generally continuous with plants evenly distributed across a relatively homogeneous scald microhabitat that was particularly extensive at Budgerum. It is significant to note that the scalds at the two grassland sites are characterised by not being a true depression as was widespread at Warnup. At both grassland sites, there was still a slight fall that would allow slow drainage following a downpour suggesting at least some parts of these sites may be a red rise lacking an A-horizon (see Discussion section).

Figure 5: Relative microrelief transects

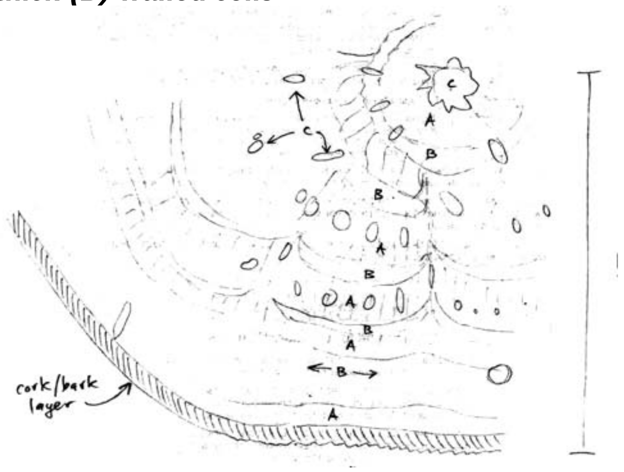
Chariot Wheels presence within 1 m radius sub-quadrats indicated by white squares



Longevity

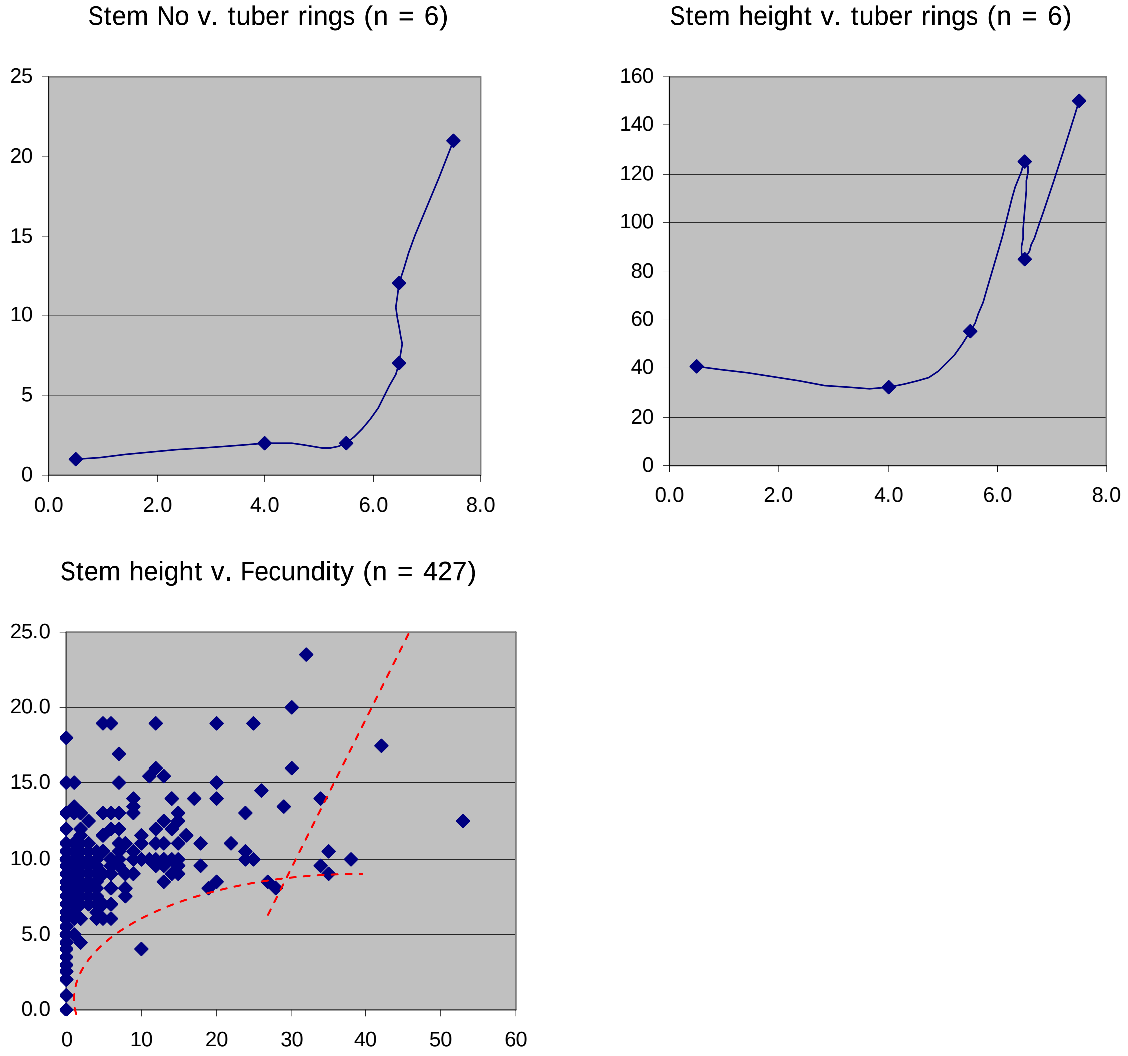
Given the plant's strict seasonal dormancy behaviour, it was assumed that the radial banding of alternate layers of small (thick-walled cells) and large (thin-walled cells) correspond respectively with the alternate annual dormancy and growth phases as found in wood growth rings (Figure 6). Thus the number of tuber double bands was presumably an estimate of plant age in years.

Figure 6: Tuber transection showing the alternate radial banding of thin (A) and thick (B) walled cells



Significant growth in either stem height or stem number does not occur until beyond the age of 5 or 6 years, after which there are rapid annual increments. Plants with six tuber rings were found to be as large as those with less than one. This suggests, plants devote upto their first 6 years developing a large tuber and associated root system for persistence and dormancy capacity before they are capable of significant above ground growth. A scatter plot of stem height against fecundity (maximum flower/seed yield per plant; n = 427) indicates plants are only capable of producing seed when stem height exceeds ~5 cm at about 5 years of age. A maximum stem height figure of ~25 cm suggests plants may only live for upto ~10 years of age (Figure 7). However, further sampling (replication in a range of size classes and sites, plus dry weight data) is required to confirm these trends as there is some evidence that the amount of microflooding may influence both growth rates and fecundity. In other words the slow growth rates observed in the plants sampled in 2003/04 could simply reflect the poor environmental conditions at the sites involved or recent years of drought or both.

Figure 7: Relationship between plant size and tuber rings



Life stage diagram

Final life stage categorisation for the 2003/04 season was undertaken after the end of the summer/autumn dormancy period after the July 2004 assessment. Four life stages were defined whereby each feeds directly into the next in the following sequence:

1. **Seeds (S):** maximum number of seeds per quadrat per year.
2. **Recruits (R):** total number of germinants that survived to resprout in the following winter per quadrat per year (approx 1 to 2 years old).
3. **Adult, Non-flowering (ANF):** total number of resprouted plants that failed to bud, flower or set seed at any point during the growing season per quadrat per year (approx 2 + years).
4. **Adult, Flowering (AF):** total number of resprouted plants that either budded, flowered or set seed at any point during the growing season per quadrat per year (approx 2 + years).

Three additional stages: transitional within a year (Germinant); life completing (Dead); or miscellaneous (Unclassified) for living plants that could not be readily classified, were also useful in the study:

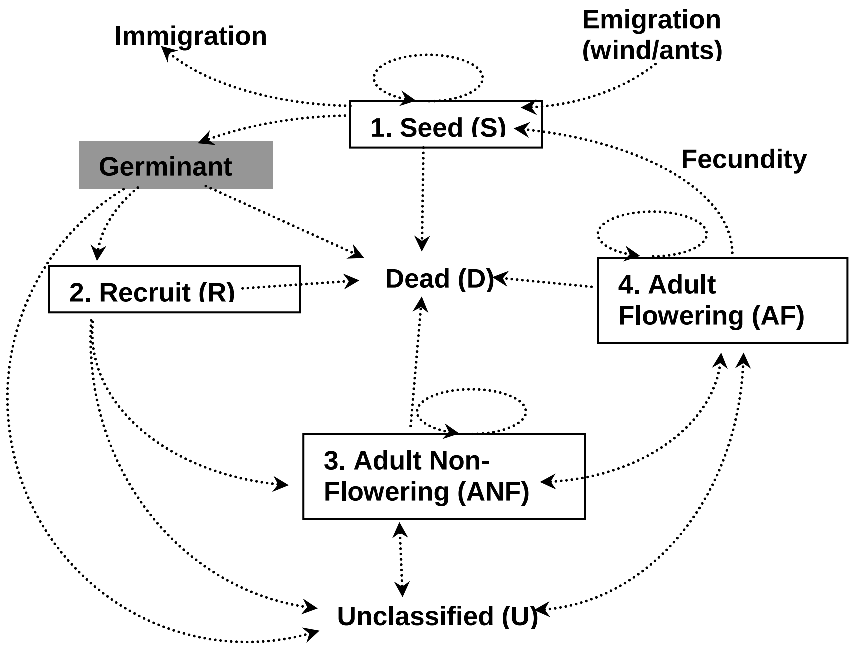
- **Germinants (G):** maximum number of germinants per quadrat per year

- **Unclassified (U):** total number of resprouted plants that could not be classified into either Adult Non-flowering, Adult Flowering or Dead categories. This was often due to lost tags or incomplete information throughout the year.
- **Dead (D):** total number of resprouted plants that did not resprout in the following winter per quadrat per year.

As the annual drought-avoiding dormancy cycle suggests, plants often took some time to reach the stage at which they were finally classifed during the study period (2003/04 season). The typical intra-seasonal cycle for established adult plants is firstly resprouting either from ground level or aerially following the first significant rains in autumn or winter (May to July), then a progression to either Adult Non-flowering or Adult Flowering through spring and early summer and finally back to Adult Non-flowering in late summer and autumn. Some plants remained in either Adult Flowering or Adult Non-flowering throughout the spring and summer period (Figure 8). Those plants that were evidently alive, but either failed to resprout or to progress beyond resprouting (plus plants with lost tags) were recorded as Unclassified.

Figure 8: Life stage diagram

Lines and arrows show the direction of movement (of individuals) within or between years. No attempt has been made here to illustrate the complexity of the dynamics of the seed phase nor to respresent the relative sizes of the movements between the different phases.



The loop arrows over the Seeds, Adult Non-flowering and Adult Flowering phases indicate that individuals can remain in the same category from one year to the next. It is possible from the longevity data that plants could stay in the Adult Non-flowering category for instance for upto 5 years beyond germination and recruitment. Although not closely examined, it is presumed the seeds that germinate (or are available to germinate in any one year) come from one of two sources: those that persist *in situ* either on or within the soil and those that emigrate in from adjacent areas or populations via wind and insect dispersal processes that peak during early summer when mature seeds are shed. Furthermore, it is presumed that those seeds shed locally but don't germinate, have either been blown away (immigration), predated by ants, are non-viable or otherwise rendered non-viable (for example) by being lost down deep soil cracks (Figure 7).

Germination has not been given a discrete phase status as it occurs as part of the broader process of recruitment. However, it has been included in the life-cycle diagram as a significant intra-seasonal process that underpins recruitment and the entire reproductive strategy. By definition, any germinant that survives until the beginning of the next season is a recruit.

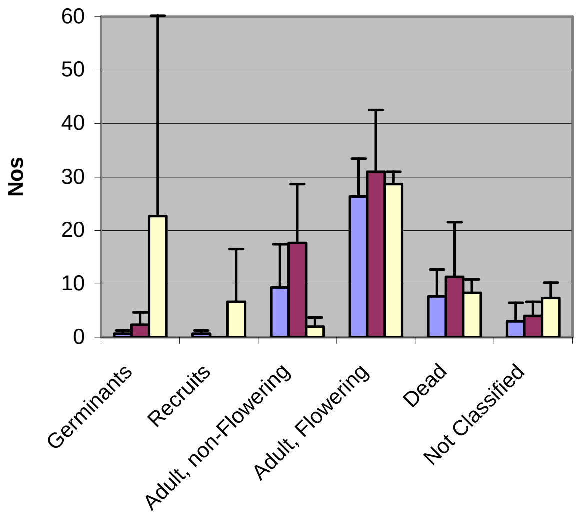
Population attributes

A total of 547 plants were marked in the 9 quadrats during the 2003/04 season from September 2003 to July 2004 (an average of ~61), comprising 77 Germinants, 43 Unclassified and 427 Flowering and Non-flowering Adults. At the end of the season (July 2004), when all plants were classified into the four life stages (excluding seeds) plus the three additional stages, the majority (47%) were Adult Flowering, 16% were Adult Non-Flowering and 4% were Recruits. The mean mortality rate was 19.2% and just under a third of the 77 germinants (29%) successfully recruited (Figure 9). Expressed as a proportion of all adult plants, the mean level of flowering was 60.4% (Appendix 6).

Pooling the data at each site, the populations were similarly structured except for the Adult Non-Flowering category and for Germination and Recuitment. Pine Grove had almost double the number of Adult Non-Flowering plants than either of the other two sites, and significant germination (and therefore recruitment) was only recorded at Warnup (Figure 9). A higher number of Unclassified plants was recorded at Warnup as some tags had been lost due to stock damage following a significant downpour earlier in the year.

Figure 9: A comparison of population structure at the three sites

Blue = Budgerum; Red = Pine Grove and Yellow = Warnup. See Sect. 3.6 for category definitions. Bars indicate standard deviations.

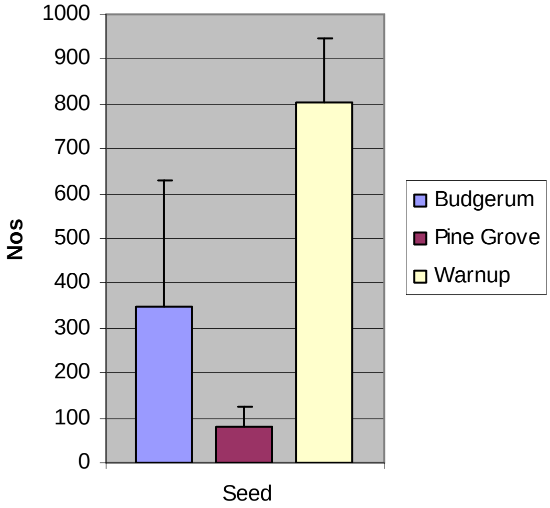


A closer examination of germination at Warnup shows that it is highly patchy in distribution (Figure 15; Appendix 6). General observation at each site suggests that the quadrat data is indicative of germination behaviour throughout each site, namely that it was absent, rare or at very low densities at Pine Grove and Budgerum, and patchy at Warnup (scattered in numerous relatively high density clumps).

Fecundity (seed production per plant) was significantly higher at Warnup (805 seeds/1m^2) compared to the two grassland sites (348 and 79 seeds/1m^2 at Budgerum and Pine Grove respectively) (Appendix 6; Figure 10) as average plant height and number of stems were broadly similar at each. The possible reasons why Warnup supported significantly more fecund plants is explored in the Discussion Section.

Figure 10: Total seed production per site

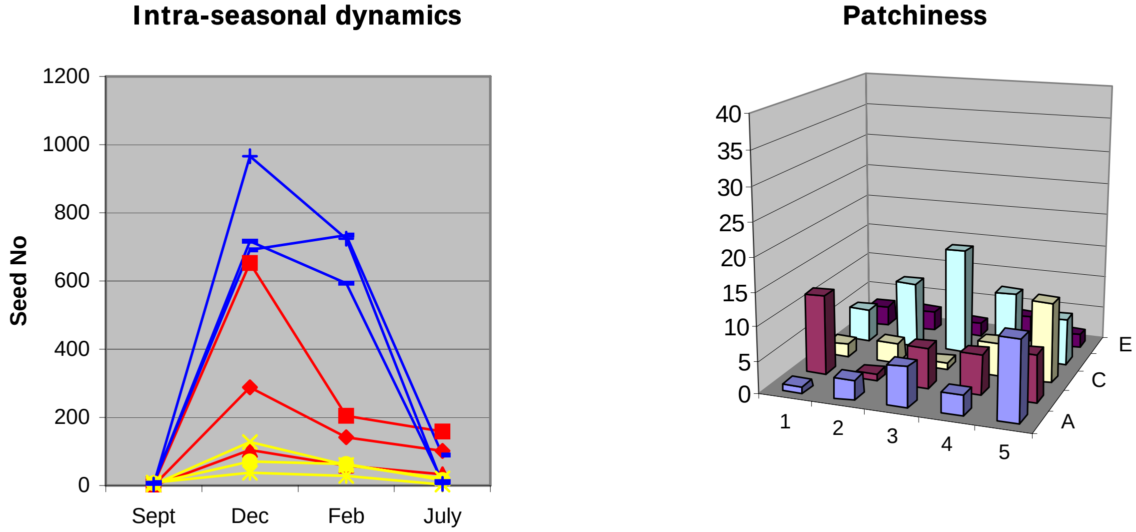
Blue = Budgerum; Red = Pine Grove and Yellow = Warnup. Bars indicate standard deviations.



Despite the influence of ant and wind dispersal, it is likely the seed density data (per 400 cm^2 sub-quadrats) is broadly reflective of plant fecundity as the patchy distribution within the quadrats broadly corresponds with the spatial distribution of the Adult Flowering plants. In other words the seed was largely falling straight to the ground and had not been either predated or blown away by the December 2003 site visit when it was peaking at all sites (Figure 11).

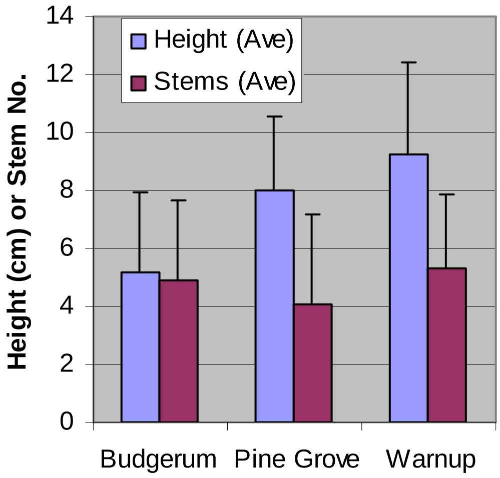
Figure 11: Seed production – seasonal and spatial distribution

Blue = Budgerum (Diamonds – Black, Squares – Blue, Triangles – Red); Red = Pine Grove (Cross – Black, Double Cross – Blue, Circle – Red); and Yellow = Warnup (Vertical Bar – Black, Horizontal Bar – Blue, Double Horizontal Bar – Red)



One possible explanation for the dramatic difference in fecundity between the three sites is plant size, possibly linked to site productivity, rainfall and microflooding or even genetics. However, average plant size (both stem number and branch height) did not vary greatly between the sites (Figure 12). This result is consistent with both the rainfall and microflooding observations.

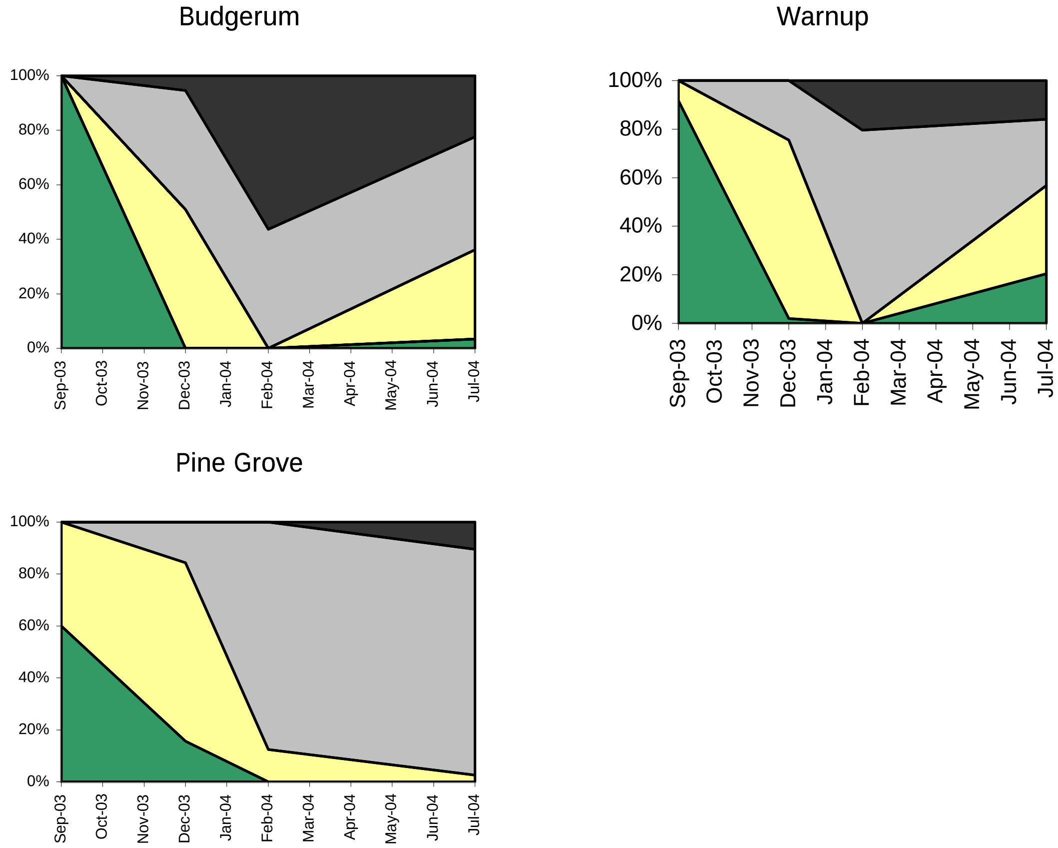
Figure 12: Plant size (stem number and height)
Bars indicate standard deviations.



Whilst Plant Health was intended as a catch all for seasonality as well as the influence of disease and other pathologies (eg. fungal, rust and invertebrate attack), it was overwhelming driven by seasonality. The data clearly reflects the annual cycle from resprouting following the first significant rains in late autumn or winter through to ‘dying back’ into dormancy over the summer months. The majority of the plants are vigorous during the spring when growth is most rapid and all plants appear to phase sequentially through all four health states during the year, with those failing to resprout from an apparent dead state during summer assumed to be completely dead. Note that the seed maturation process appears to happen simultaneously with a dramatic deterioriation in plant health by December on their way to summer dormancy when stems appear either entirely dead or in poor condition (Figures 11 and 13). Presumably the differential plant health behaviour observed both within and between sites is the consequence of a combination of factors (rainfall, microflooding, stochastity etc.) but could also include disease. For example an unidentified rust was observed on the leaves of Chariot Wheels at Warnup (Deanna Marshall pers. comm.). The role of such pathogens in the life history of Chariot Wheels is unknown.

Figure 13: Plant health for black replicate quadrats at each site

Green = Vigourous; Yellow = Fair; Grey = Poor; and Black = Dead



Presumably much of the branch loss recorded as browsing, that may have resulted from various forms of grazing by stock or invertebrates, was more attributable to the strong seasonal growth-dormancy cycle described previously as the highest levels of browsing were observed in December and February when plants are rapidly deteriorating into seasonal dormancy. Grazing regime data or scat density counts will likely give a far more accurate picture of stock grazing pressure at each quadrat than counting the number of 'browsed' stems. If grazing levels do affect browsing as measured in this study, it is likely to be more evident during the rapid growth phase in spring, when it is also more likely to have negative consequences for fecundity.

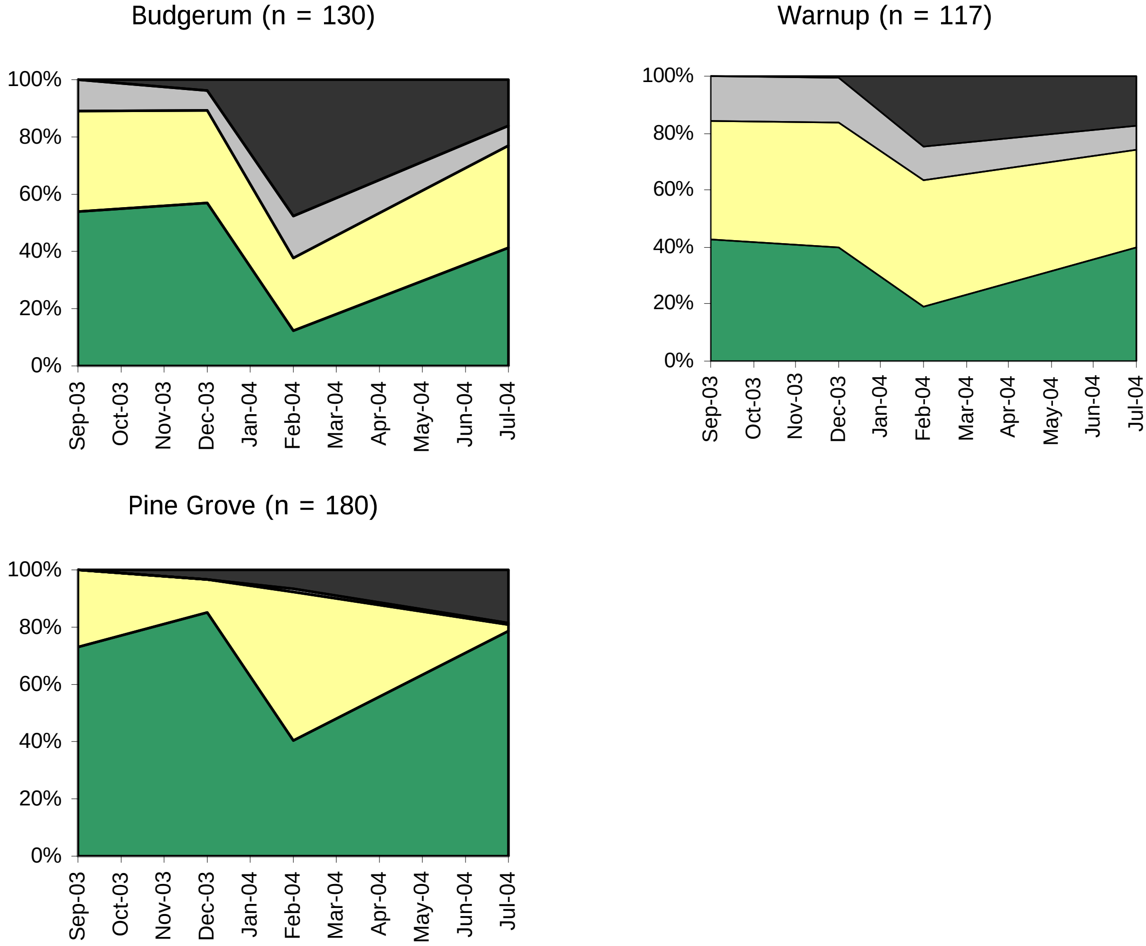
Plant Form appears to be driven in part by seasonality and part by plant density, especially the proportion of erect individuals. Pine Grove had the highest proportion of erect plants (excluding summer) (~80%) and the highest density (n = 180), whilst Warnup had the lowest proportion of erect plants (~40%) and the lowest density (n = 117). Budgerum was in between in both respects. This result accords with incidental observations of generally up-right patches of plants where numbers are high and plants tending to be prostrate and sprawling where numbers are relatively low. This is an interesting result because it suggests that Chariot Wheels is not always just trying to survive in the apparently harsh conditions of the Riverina and Wimmera. At least in some places and at some times, resources (water) are plentiful enough to produce competition dependent behaviour in populations. This conclusion is further supported when looking at grazing levels as comparison of plant form data with stocking levels shows no correlation (Table 1 and Figure 14).

As these patterns become modified over the summer months, when plants move into dormancy and are most vulnerable to mortality, there is evidence to suggest some sequential phase movement. In other words plants don't shift suddenly from their dominant form state into the dead category during dormancy, at least some plants tend to shift through transitional phases (eg. Erect to Decumbent to Dead rather than Erect to Dead). Other plants don't even make it to

Dead and persist through summer either in the decumbent or prostrate categories, apparently robust enough to survive this harsh period without stems dying back completely (Figure 14).

Figure 14: Plant form for all quadrats at each site

Green = Erect; Yellow = Decumbent; Grey = Prostrate; and Black = Dead



Finite rate of increase

Finite Rate of Increase (FRI) ranged from 0.76 to 1.27, but was on average well below 1.0 (0.86) (Appendix 6). In fact, FRI exceeded 1.0 at only one quadrat – Warnup Red – the only place where germination and recruitment was able to off-set the consistently high level of mortality due to the unusually dry summer (Figures 15 and 16).

As is typical of such perennial forbs where recruitment is episodic, the FRI data show that 2003/04 was not a recruitment year (see Menges and Dolan (1998) – Example of *Silene regia* where the FRI exceeded 1.0 only when populations were actively recruiting). Given that the rainfall during 2003/04 was just above the long-term average for 2 of the sites (Figure 3), episodic recruitment may either require well above average rainfall (which occurred only 4 to 6 times since 1980) or some other rainfall pattern that occurs more frequently.

Figure 15: Mortality vs. Recruitment for each of the three quadrats at each site
Blue Bars = Budgerum; Red Bars = Pine Grove; and Yellow Bars = Warnup

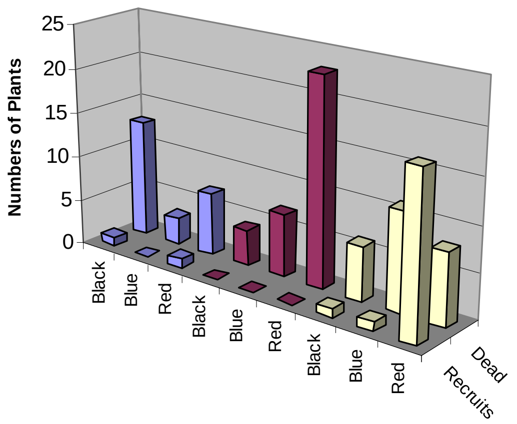
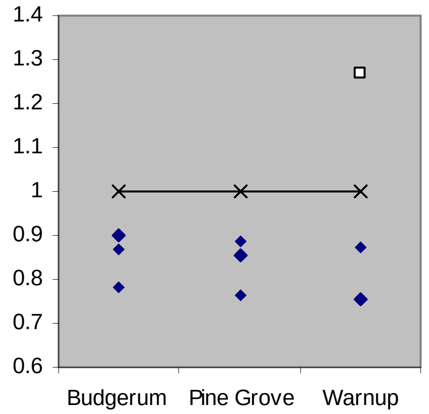


Figure 16: Finite Rate of Increase for each of the three quadrats at each site
Blue diamonds represent FRI < 1 and the white square FRI > 1 – the only quadrat that experienced recruitment in 03/04



4 Discussion

Environmental niche

The near exclusive occupation of particular microhabitats at each site (especially in the context of the family *Chenopodiaceae*) suggests Chariot Wheels has evolved a specialized reproductive strategy. As discussed earlier, the most plausible explanation is seed dormancy that is broken by microflooding with the leaching of germination inhibitors from the fruiting perianth. The nature of the appropriate microflooding regime is controlled by the time taken to leach the inhibitors and the point at which prolonged and deep inundation results in a significant change in vegetation (ie. wetland). Although not present during any of the four site visits, microflooding was only observed during 2003/04 at Warnup – the only one of the three sites where any significant germination and recruitment was observed.

Microrelief and soil profile data revealed further significant differences between Warnup and the two grassland sites. Warnup has greater microrelief complexity, while the two grassland sites appear to be in degraded condition dominated by a homogeneous scald microhabitat with continuous, non-patchy populations. It is suggested that the scalds of the grassland sites are marginal habitats that have been created by post-settlement management. Either these sites formerly supported complex gilgai microrelief (similar to that at Warnup) that has been simplified by cultivation and/or over grazing or Chariot Wheels has effectively invaded these areas from nearby when the scalding created temporarily suitable habitat by changing the microrelief and reducing plant competition. Chariot Wheels would then have established itself in these 'new' areas as soon as there was sufficient rainfall. Whilst the very large grassland populations have apparently resulted from this process (perhaps >200,000 plants at Budgerum for example), the microhabitat homogeneity is problematic. Effectively these sites are putting all their 'eggs in one basket' with persistence dependent on the scald microhabitat remaining reproductively viable. The absence of significant germination in 2003 at both Pine Grove and Budgerum suggests these populations struggle to reproduce in dry years. In the context of a climate change scenario (which could increase the frequency of drought) the microhabitat homogeneity of the grassland sites could result in rapid population decline or even extinction.

In contrast, the microhabitat heterogeneity of Warnup, where there are numerous types of depressions and shelfs with different microflooding potential and characteristics, there is a greater chance that at least one of the microhabitats will be (reproductively) viable in any one year (as was observed in 2003). Even in the context of drought, the brief downfalls that occur can result in sufficient microflooding in some places to produce germinants and recruits. According to this model microhabitat heterogeneity increases the probability of population persistence and implies a complex dynamic in either spatial patterning of the population or its reproductive success driven by the interaction between microrelief and climate, the net affect of which is a decreased likelihood of extinction and increased resilience.

Microflooding may not just play a role in the plant's reproductive strategy, it may also influence vegetative growth rates, fecundity and even mortality. Although microflooding was not significant in 2003 at the depressions sampled at Warnup, these adult plants were generally larger (max stem height and stem number) and more fecund than those at both grassland sites. It is also possible that the duration, frequency and timing of microflooding could influence the persistence of adult tubers through seasonal dormancy over summer. Even though the 2003/04 summer was particularly dry and resulted in significant mortality at all three sites, this loss was more than off-set by significant germination and recruitment in some patches at Warnup – the only site were microflooding was observed at the beginning of the season in winter 2003.

Population ecology

Recruitment had a very significant impact on FRI with only those populations with episodic/patchy recruitment achieving an FRI > 1.0. The other important component of the FRI equation is mortality, which was consistently high throughout in part due to the abnormally dry summer (1 in 30 year extreme). The net affect of these factors is that overall the FRI average out at a very low 0.86. However, this result is likely an underestimate as true rates of mortality can only be determined by monitoring the fate of these plants in subsequent years. Obviously if the populations maintain the FRI observed in 2003/04 they will disappear very quickly. Clearly this is unlikely to reflect reality. Consequently, further years of demographic monitoring is required to obtain a more realistic understanding of growth rates and extinction probabilities.

As is typical of perennial grassland forbs like Chariot Wheels, recruitment is likely to be episodic and patchy – linked to climate or disturbance events (Menges and Dolan 1998). Clearly 2003/04 was not a recruitment year, at least at the two grassland sites. It is speculated that in wetter years mortality is likely to be lower, and flowering and fecundity increased along with more germination and even higher rates of recruitment. Given that mean annual rainfall for 2003 was slightly above average at the closest permanent weather stations, episodic recruitment is probably more linked to the timing and size of rainfall events rather than annual totals. Further monitoring would also help to describe the stochastic nature of recruitment.

There is some evidence that population size and isolation affects fitness. The Pine Grove population was the smallest and most isolated of the three and clearly had the lowest fecundity which was not apparently linked to plant size, rainfall or stock grazing. Genetic studies would be required to determine if this population is suffering from inbreeding depression whereby reproductive fitness has been reduced by low genetic diversity.

It is unclear whether Chariot Wheels forms a soil seed bank, although it seems likely it does not. The high seed production and dispersal dynamics observed at all sites suggests most seed is either blown away or predated by ants. Either way, despite prolific seed crops at some sites, little seed apparently persists *in situ* from one year to the next. Whilst it is possible a fraction of the seed crop falls down minute cracks in the soil or is transported into subterranean chambers by ants, the fragility of the perianth casing and the small size of the seed suggests persistence beyond the following season is unlikely. The perianth structure serves the dual role of aiding wind dispersal and controlling dormancy, critical for the plant's reproductive ecology. It is also very fragile and readily breaks down in the field. Once it has dessicated, these functions are no longer possible and the seed is vulnerable to death and predation. If, however, it does germinate the following season in an unfavourable site (ie. not subject to microflooding) the seedling would be much more vulnerable to competition and less likely to survive.

Conservation and agriculture

The only evident correlation between grazing levels and demographic attributes of plant populations was for mortality. Plants are apparently vulnerable to grazing during the summer to autumn dormancy phase and presumably trampling could exaggerate 'normal' mortality rates, particularly in unusually dry years such as 2003/04. But further work involving exclosures, replication and more time would be required to investigate the reality of this correlation.

The proportion of adults flowering, fecundity, plant form, plant health, germination and recruitment all appeared to be independent of grazing pressure. However, this may only be due to the fact that grazing was excluded from all three sites during the winter and spring periods. It is quite possible that in an episodic recruitment year, grazing pressure would exert some influence on these attributes through either trampling or direct browsing.

As with the population ecology data more sites and time are required to fully understand the relationship to stock grazing. Multivariate analyses are also required that factor in variables such as population size and isolation, genetic structure, microhabitat heterogeneity, habitat condition (ie. area, species richness and weediness) and *in situ* rainfall patterns.

Historical information (such as old herbarium records, past management regimes or rainfall records) is useful but may be misleading in future scenario modeling, especially climate change. Whilst the impacts of the type of grazing regimes typical of these sites (ie. rotational and low stocking levels) may have been historically off-set by frequent and prolific episodic recruitment, it may become more crucial under climate change.

In the big picture, species conservation depends necessarily on the conservation of individual populations. Clearly the extant distribution of remnant Chariot Wheels populations has resulted from widespread post-European settlement land clearing. Over 95% of the original extent of many habitat types in both the Wimmera and Riverina have been lost (DSE 2004). Land clearing not only destroys habitat but it also has the affect of isolating and degrading those that happen to survive. As land clearing continues today and the vast majority of remnant populations occur on unprotected freehold land, it is reasonable to suggest that habitat destruction remains Chariot Wheels' biggest threat. The resulting landscape-level fragmentation and degradation is often considered by ecologists as a form of ecosystem stress – correlated with a range of variables such as habitat size, weediness, species-richness, isolation and so on (Gunderson and Holling 2002). The historical biogeography of Chariot Wheels suggests that it is ecosystem stress rather than *in situ* processes (ie. stock grazing, especially if consistent with traditional practice) that represents the biggest short and long term threat. In a sense ecosystem stress is about land use change. Those areas cleared for cropping and irrigation have under gone massive change whilst other areas have been modified to a far lesser degree. These less modified areas are fragments of the original landscape and biota. Whilst some species are known to have disappeared early on, most survive in these fragments, albeit often as threatened species (Briggs and Leigh 1995). Chariot Wheels is a typical example of a once common species that has become threatened by ecosystem stress driven by post-settlement human land use. Chariot Wheels has apparently survived very well on remnants of original habitat even when subject to various levels of stock grazing. Some populations today are numbered in the hundreds of thousands (eg. Budgerum). The decision however to shift from this traditional practice to more 'productive' or 'profitable' land use systems will almost certainly wipe out these populations as sure as it wipes out its grassland or savannah habitat. The question is how far can land use change be pushed before Chariot Wheels conservation becomes marginal? Given we have no choice but to continue to achieve at least a proportion of biodiversity conservation in the context of private enterprise this is an important question, especially considering the need for industry to compete and survive in global markets. However, in tackling this question we must also commit to the following additional measures in order to minimise the risk of extinction: (1) identify all extant sites; (2) prevent further habitat loss or land use change; (3) prevent the degradation of habitat; and (4) understand reproductive biology and population trends. In the long term strategic habitat restoration may also be required to conservation particular populations.

Further research

One year of data collection is no basis on which conclusions can be drawn about population ecology. Clearly further years of work and data collection are required to build confidence about the observations made during this study. Many studies have concluded that temporal variation often has a far greater influence on population dynamics and structure than spatial, demographic variation or any other factor (Gurevitch *et al.* 2002). Extinction probability modelling and other stage-based techniques cannot be undertaken with less than two years of data. Two years is required to track the stage transitions in populations by monitoring the behaviour of individual plants in two consecutive years. Repeating this process over longer time frames would help to determine the influence of stochastic and episodic events that are likely to factor strongly in the ecology of semi-arid systems where climatic patterns especially are less predictable.

A further issue is how do the results inform management? Whilst monitoring individual populations will help to determine whether or not they are stable, it will not help to determine why and, more importantly, what should be done to rectify the problem. Such answers can only be supplied by controlled comparisons whereby the performance of populations under different management treatments are contrasted. Given the long-term aim of the ESAI is sustainability under stock grazing, and in particular defining the limits of sustainability, the impact of various grazing regimes would need to be assessed. The key factors such as stock type, grazing system (rotational vs. continuous systems), and stocking level would all need to be compared with exclosure (no grazing) and the *status quo*. Although it should be noted that *status quo* is highly variable and extremely difficult to define in more than general terms. Identification of the appropriate grazing regimes and monitoring population performance over at least two years would be the primary aim of this extra research. The baseline data provided by demographic monitoring during 2003/04 would help to efficiently focus the monitoring effort.

In order to improve the confidence of the outcomes emerging from the research proposed above, it will be necessary to sample a greater diversity of sites and to replicate the treatments to a greater degree than was possible in this study. Managers could then be assured that the behaviours observed and the recommendations emerging will be applicable to a greater range of populations.

Whilst population performance research will help to understand how populations behave under different conditions it will not help to define the processes that determine or control the trends observed. A good example is seed germination ecology. It is clear from this study that recruitment is fundamental to population and species persistence, however, without understanding how this process works it will not be possible to understand relationships with management. Only simple hypotheses have been presented in this limited study – ie. microflooding controlled seed dormancy. Four key aspects of reproductive biology would be worthy of investigation and all focus on seed germination ecology and recruitment: (1) How long can seed persist in the field anddoes Chariot Wheels form a seed bank? If so, what controls dynamics? (2) Do seeds actually exhibit dormancy? If so, is it controlled by chemical inhibitors in the perianth that are leached out by water and is prolonged immersion such as that expected under microflooding required to trigger germination in the field? (3) Is seed production and seed viability related to population size? Is this the cause of poor germination and therefore poor recruitment at some populations? (4) How sensitive is recruitment to competition from other vegetation, especially weeds such as annual grasses?

The soil seed bank question would require a lab experiment whereby soil samples are assessed for the presence of all viable seed as well as field-based experiments testing for seed longevity. The dormancy question would require field-based experiments whereby the response of known quantities of viable seed with and without microflooding would be contrasted in areas of suitable habitat without Chariot Wheels. The third question relating to possible inbreeding depression affects could be simply addressed by assessing the viability and quantities of seed collected from various populations of known size. Viability testing can be readily undertaken in controlled lab conditions. The final question of sensitivity to competition would best be undertaken in the field whereby seed of known viability is artificially introduced to areas of suitable habitat (but where Chariot Wheels is known to be absent) with and without weed seed.

Management suggestions

Although it is suggested grazing may have an impact on mortality rates at some sites and could influence breeding performance, no evidence emerged in this limited study to suggest stock grazing negatively or otherwise affects Chariot Wheels. All the anecdotal and distribution information points to the plant being rare (threatened) because of habitat destruction and fragmentation. The large population levels recorded at many sites strongly suggests grazing is compatible with Chariot Wheels persistence at least over post-European settlement time scales. Exclosures would be useful in demonstrating the nature of the relationship between grazing and the species ecology. Relatively long time scales (5-10 years+) would be necessary to draw meaningful conclusions as it would be necessary to separate short-term processes such as trampling and browsing from those operating over the long-term like weed invasion that reduces habitat area and quality.

As with many grassland conservation reserves in northern Victoria such asTerrick Terrick National Park((Parks Victoria 2004) **a cautionary approach to management is generally recommended for Chariot Wheels conservation whereby *status quo* management is maintained until or unless clear alternatives are identified by reliable research.**

Although in the case of Terrick Terrick National Park where biomass control is implicated in conservation management, for Chariot Wheels the relationship with grazing is less clear. It is equally possible, for instance, that the current grazing regimes utilized have either a benign or correlated (positive or negative) influence on populations and that this relationship may have been different in the past and that it might change in the future.

This management approach is also suggested because it is consistent with the objectives of the ESAI project that aims to investigate the relationship between agriculture and conservation. Ideally the chosen case studies aim to define the limits of tolerance, between which productive agriculture and conservation overlap or are compatible. However, this objective can only be achieved with long-term data and sophisticated experiments. In the absence of such information, species historical biogeography suggests the regimes utilized at sites containing remnant populations (especially large ones) are probably within the presumed range of compatibility, a reasonable assumption until or unless reliable contrary information is obtained. Clearly this approach requires that some monitoring and research is undertaken. Thus it is recommended to **continue monitoring population performance at the three sites established for this study and expand the project by undertaking the suggested further research work in order to understand the compatibility of Chariot Wheels conservation with different agricultural regimes**. At least four years of data (2 by 2 years dynamics cycles) is recommended for existing monitoring points (ie. 2003-07) and equivalent for any new experiments or sites (eg. 2005-09), although collection over a longer term is highly desirable. Some of the reproductive ecology research suggested could be undertaken with a 12 month period.

On the basis of grazing patterns recorded during this study, *status quo* management is rotational sheep grazing up to 0.72 DSE/ha/yr with spelling between August and December with individual grazing events up to ~2.5 DSE/ha maintained for up to 5 months. As no historical research was undertaken, these figures do not necessarily reflect traditional practice, although anecdotally these figures are broadly indicative of what is practiced in equivalent non-Chariot Wheels sites elsewhere in northern Victoria. For example stocking levels are cited as ~1 DSE/ha/yr and cattle are often used instead of sheep on Northern Plains Grassland remnants (Foreman 1996). However, at this bigger scale, so called *status quo* regimes (those used on remnant habitat and presumed to have been consistently practiced since European settlement) are so variable as to render the idea meaningless. Caution needs to be applied when considering the notion. The recommended regime is potentially on the lower end of the compatibility range and collecting further data on grazing patterns plus investigating historical stock management would be used to better understand the nature of *status quo* management for Chariot Wheels.

Consistent with the earlier discussion on the notion of ecosystem stress, the protection of extant habitat is paramount for Chariot Wheels conservation. Any actions that directly destroy or severely degrade habitat such as cropping, clearing or fertiliser application cannot be considered compatible and must be avoided at all costs. Obviously this message is clear for managers of known populations such as the three used in this study, however, it is likely there are further unknown populations. **Locating these additional sites as well as clearly communicating the importance of avoiding incompatible actions** is strongly recommended. Although this recommendation is more suited to conservation agencies, interested individuals, or groups (such as Landcare groups and conservation NGOs) may wish to participate in campaigns to help locate and protect local populations. This protect-what-is-left strategy is built on the view that it is ecologically and economically prudent to protect extant populations and work out how to enhance any under-performers rather attempt to create entirely new ones.

5 Conclusions

Chariot Wheels was found to be a long-lived plant (~10 years) with a relatively high rate of mortality (mean = 19.2% in 03/04) attributed to a relatively dry summer and an over estimation error linked to the brevity of the project. Although variable, just over 60% (60.4%) of the adult plants flowered. Germination was uncommon and highly patchy (apparently linked to microflooding), but where it did occur, a significant proportion survived the first summer and recruited (28.6%).

On the basis of the population growth rates calculated during 2003/04, Chariot Wheels will struggle to persist at two of the three study sites. The poorest population performance was recorded where numbers were lowest and the site most isolated. However, further monitoring is required before growth rates can be confidently determined. The fact that all populations have persisted under post-European grazing regimes suggests traditional or *status quo* management is broadly compatible with Chariot Wheels conservation.

On the basis of the grazing recorded throughout 2003/04, *status quo* management was described as rotational sheep grazing up to 0.72 DSE/ha/yr with spelling over spring. Although there was little evidence the stock were directly affecting the populations monitored.

A number of suggestions were made regarding the management of remnant populations and for future research future. These include: continued monitoring; an expanded research program focused on different management regimes, seed germination ecology and recruitment; the general maintenance of *status quo* management; and identifying additional remnant populations and ensuring none are destroyed by incompatible actions.

Management options, including some of the above suggestions, are to be developed jointly with DPI Agriculture staff, land-holders and other key stakeholders in the final phase of the project.

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Appendices

Appendix 1: Quadrat location and surface soil

All EVC = Ecological Vegetation Class; NPGL = Northern Plains Grassland;

	Site	Replicate	EVC	Position	Soil_Surface	Comments
1	Pine Grove	Blue	NPGL	Scald	Surface Crust	Soil moist but slightly crumbly; difficult to remove from auger
2	Pine Grove	Red	NPGL	Scald	Surface Crust to Surface Flake	*Maireana pentagona* in small numbers nearby
3	Pine Grove	Black	NPGL	Scald to Red Rise	Hard Setting to Surface Crust	
4	Pine Grove	Add1	NPGL	Red Rise	Hard Setting to Surface Crust	Soil very wet and sticky
5	Pine Grove	Add2	NPGL(wet)	Gilgai Depression	Self Mulching to Cracking	Soil very moist but crumbly; difficult to remove from auger
6	Budgerum	Blue	NPGL(annual)	Red Scald	Surface Crust to Surface Flake	
7	Budgerum	Red	NPGL(annual)	Red Scald	Surface Crust to Surface Flake	
8	Budgerum	Black	NPGL(annual)	Cracking Scald	Surface Crust to Surface Flake	Soil moist but crumbly; easy to remove from auger; very firm at depth
9	Budgerum	Add1	NPGL(annual)	Red Rise	Hard Setting to Surface Crust	
10	Budgerum	Add2	NPGL(wet)	Gilgai Depression	Firm to Hard Setting	Floristically, highly mixed
11	Warnup	Blue	? (Wimmera GWL)	Pale Shelf	Hard Setting to Firm	Soil slightly moist and initially fell out of auger easily; harder at depth
12	Warnup	Red	? (Wimmera GWL)	Grey Scald to Pale Shelf	Hard Setting to Surface Crust	Both depressions apparently flooded earlier in winter
13	Warnup	Black	? (Wimmera GWL)	Brown/Grey Scald	Hard Setting to Surface Crust	Soil slightly moist and initially fell out of auger easily; harder at depth
14	Warnup	Add1	? (Wimmera GWL)	Grey Puff	Firm (soft in places)	Soil very crumbly and dry; easy to remove from auger

Appendix 2: Quadrat vegetation structure and floristics

All taxonomy follows Young et al. (2002); All figures are percentage (overlapping) cover.
Asterisk denotes weed or naturalized species.

	Pine Grove					Budgerum					Warnup			
Species/Unit	Blue	Red	Black	Additional 1	Additional 2	Blue	Red	Black	Additional 1	Additional 2	Blue	Red	Black	Additional 1
Bare Ground	30	70	90	30	10	80	40	80	30	10	30	70	90	50
Bryophytes/Lichens/Algae	<5	<10	<5	10	1	10	<10	<5	10	<10	<5	<5	<5	5
Organic Letter	<5	1	<1	<5	10	<1	<1	1	<1	<5	<5	1	>1	<5
Rocks/Stones	0	0	<1	0	0	0	0	0	0	0	0	0	<1	0
Water	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Weeds (total)	50	10	1	40	90	<2	<1	1	5	60	50	10	1	40
Indigenous (total)	20	20	<10	30	<10	20	60	20	65	30	20	20	<10	10
**Arctotheca calendula*					20					<5				
**Bromus rubens*	<1	<1									<1	<1		<1
**Cotula bipinnata*				<5	<5									
**Critesion marinum*		<1	<1											
**Erodium botrys*				<5	20									
**Gynandriris setifolia*				<1										
**Hedypnois cretica*										<5				
**Hypochaeris glabra*				<1	<5									
**Hypochaeris radicata*					1									
**Lolium rigidum*		5	<1	<5	40	<2		1	1	30		1	1	
**Medicago minima*	5	<1		<1			<1		2	10	5	<1		30
**Medicago truncatula*								1	2	10				
**Plantago coronopus*				<1										
**Poa bulbosa*	45	5									45	5		5
**Polypogon monospeliensis*			<1										<1	
**Romulea minutiflora*				<10						1				
**Spergularia rubra*	<5	1	<1			<2					1	1	1	
**Trifolium sp.*					<5									
**Vulpia sp.*		<1	<1										<1	
Atriplex semibaccata		<1										<1		1
Atriplex suberecta	<1	<1	<1											
Austrodanthonia caespitosa		1										1		
Austrodanthonia setacea	<1	1						<1	<1					
Austrodanthonia sp.				<5		1	1							
Austrostipa blackii														1
Austrostipa gibbosa				<1										
Austrostipa nodosa														1
Austrostipa scabra	5						<1				1			1
Brachyscome linearloba						<1	1	<1	1	<1				
Brassicaceae sp. (Prost)						5		<1						
Bulbine bulbosa				<1										
Bulbine semibarbata							<1		<1	<1				
Crassula macrantha	<1	<1	<1	<1			<1		<1	1	<1	<1	<1	
Crassula sieberiana	<1	<1		<1			<1	<1		<1	<1	<1		
Daucus glochidiatus								1	<1					<1
Enteropogon acicularis	<1	<1		1	<5		<1		<1	1	<1	<1		<1
Eragostis dielsii	<1													
Eriochlamys behrii				<1										
Goodenia pusillifora	1	<1		<5			5		2	<2	1	<1		1
Homopholis proluta		<1			1									
Hyalosperma glutinosum		1				5	30	<5	50	1		1		<1
Hypoxis glabella	<1					<1	1	<1	2	<1	<1			
Isoetopsis graminifolia		1		<1			1	<1	1	1		1		
Isolepis sp.										<1				
Maireana cheellii	10	10	<10			10	2	<5			10	10	<10	
Maireana enchylaenoides														
Maireana excavata	<1			1					1					1
Maireana humillima	1										1			
Maireana pentagona	5	2		1			<1	1			5	<2		
Maireana rhohlarchii		<1										<1		2
Myriocephalus rhizocephalus			<1							<1			<1	
Oxalis perennans					1									

Plantago hispida							<1	<1		1				
Pogonolepis muelleriana		<1		1		1	1	2	<1			<1		
Ranunculus sessiliflorus										1				
Rhodanthe corymbiflora		<1			1	<1	1	1	1	<5		<1		<1
Rhodanthe pygmaea						<1	5	<1		1				<1
Sclerochlamys brachyptera						<1		<1						
Sclerolaena diacantha		1										1		1
Sida corrugata				<1					1	<1				
Exotic richness	**5**	**7**	**5**	**8**	**7**	**2**	**1**	**2**	**3**	**6**	**4**	**5**	**4**	**3**
Indigenous richness	**13**	**17**	**4**	**13**	**4**	**10**	**17**	**15**	**14**	**16**	**9**	**14**	**3**	**13**
Species richness	**18**	**24**	**9**	**21**	**11**	**12**	**18**	**17**	**17**	**22**	**13**	**19**	**7**	**16**

Appendix 3: Quadrat vegetation structure and floristics

All soil taxonomy follows McDonald (1984) and the dispersion test is from Chapman and Murphy (1991)

	Site	Date Sampled	Replicate	Horizon	Field Texture	Moist Colour	pH	Dispersion
1	Pine Grove	16/09/03	Blue	Surface	Medium Clay	5YR4/4 (reddish brown)	6.0	Slaking within 2-3 mins; collapsed within mins
2	Pine Grove	16/09/03	Blue	0 to 10	Medium Clay (has fine sand)	2.5YR4/5 (reddish brown to red)	6.0	N/A
3	Pine Grove	16/09/03	Blue	10 to 15	Medium Clay	2.5YR4/6	6.5	N/A
4	Pine Grove	16/09/03	Blue	15 to 20	Heavy Clay	2.5YR4/6	6.5	N/A
5	Pine Grove	16/09/03	Add1	Surface	Fine Sandy Loam	7.5YR4/5	5.0	No slaking; no real dispersion
6	Pine Grove	16/09/03	Add1	0 to 10	Light Clay (has some fine sand)	7.5YR4/6	5.5	N/A
7	Pine Grove	16/09/03	Add1	10 to 15	Medium Clay	7.5YR3/6 (strong brown)	6.0	N/A
8	Pine Grove	16/09/03	Add1	15 to 20	Medium Clay	7.5YR3/6 (strong brown)	6.0	N/A
9	Pine Grove	16/09/03	Add1	20 to 25	Heavy Clay	7.5YR3/6 (strong brown)	6.5	N/A
10	Pine Grove	16/09/03	Add2	0 to 10	Medium Clay	10YR3/4	5.5 to 6.0	No real slaking; little bit of clouding (very sticky)
11	Pine Grove	16/09/03	Add2	10 to 20	Medium Clay	7.5YR3/4	6.0	N/A
12	Warnup	18/09/03	Black	Surface	Light Clay	10YR4/2	5.5 to 6.0	Slaking within first few mins; cloudy
13	Warnup	18/09/03	Black	0 to 10	Light Clay	10YR3/1 (very dark grey)	6.0	N/A
14	Warnup	18/09/03	Black	10 to 15	Light Clay (fine sand present)	10YR4/1	6.0	N/A
15	Warnup	18/09/03	Black	15 to 20	Light Clay	10YR4/1	6.5	N/A
16	Warnup	18/09/03	Blue	Surface	Light Clay	10YR3/2	5.5	No slaking; a little bit cloudy
17	Warnup	18/09/03	Blue	0 to 10	Medium Clay	10YR3/2	6.0	N/A
18	Warnup	18/09/03	Blue	10 to 15	Medium Clay	10YR3/2	9.0	N/A
19	Warnup	18/09/03	Blue	15 to 20	Heavy Clay	10YR3/2	9.0	N/A
20	Warnup	18/09/03	Add1	Surface	Light Clay	10YR4/2	6.5	No slaking; almost cloudy
21	Warnup	18/09/03	Add1	0 to 10	Light Clay	10YR5/2 (greyish brown)	8.0	N/A
22	Warnup	18/09/03	Add1	10 to 15	Medium Clay	10YR5/2 (greyish brown)	8.0	N/A
23	Warnup	18/09/03	Add1	15 to 20	Light Clay	10YR5/2 (greyish brown)	8.0	N/A
24	Budgerum	17/09/03	Add1	Surface	Light Clay	7.5YR4/4 (brown)	6.0	Slaking within 10-20 mins; no clouding
25	Budgerum	17/09/03	Add1	0 to 10	Medium Clay	7.5YR4/4 (brown)	6.0	N/A
26	Budgerum	17/09/03	Add1	10 to 15	Heavy Clay	7.5YR4/4 (brown)	6.5	N/A
27	Budgerum	17/09/03	Add1	15 to 20	Heavy Clay	5YR4/4 (reddish brown)	7.5	N/A
28	Budgerum	17/09/03	Add2	Surface	Sandy Clay Loam	10YR4/2 (dark greyish brown)	5.0	Slaking with 5 mins; some clouding
29	Budgerum	17/09/03	Add2	0 to 5	Light Clay	10YR5/3 (brown)	5.5	N/A
30	Budgerum	17/09/03	Add2	5 to 15	Medium Clay	7.5YR4/3 (brown)	6.0	N/A
31	Budgerum	17/09/03	Add2	15 to 20	N/A	7.5YR5/3	N/A	N/A

32	Budgerum	17/09/03	Red	Surface	Medium Clay	7.5YR4/4 (brown)	6.0	No slaking within 10-20 mins; no clouding
33	Budgerum	17/09/03	Red	0 to 10	Medium Clay	2.5YR4/4 (reddish brown)	6.5	N/A
34	Budgerum	17/09/03	Red	10 to 15	Medium Clay	5YR4/4 (reddish Brown)	7.0	N/A
35	Budgerum	17/09/03	Red	15 to 20	Medium to Heavy Clay	5YR4/4 (reddish Brown)	7.5	N/A

Appendix 4: Quadrat vegetation structure and floristics

S = Seed; G = Germinant; R = Recruit; ANF = Adult Non-flowering; Adult Flowering;
D = Dead; U = unclassified; N03 = total population in 2003; N04 = total population in 2004;
FRI = Finite Rate of Increase; %F = Percentage of adult plants flowering;
and %M = Percentage of adult plant mortality

	S	G	R	ANF	AF	D			D	U	N03	N04	FRI	%F	%M
						G	ANF or R	AF	Tot						
C_Black	288	1	1	8	34	0	3	10	13	1	55	43	0.78	61.8	23.6
C_Blue	653	0	0	2	25	0	1	2	3	1	30	27	0.90	83.3	10.0
C_Red	104	1	1	18	20	0	4	3	7	7	45	39	0.87	44.4	15.6
Budgerum	**1045**	**2**	**2**	**28**	**79**	**0**	**8**	**15**	**23**	**9**	**130**	**109**	**0.84**	**60.8**	**17.7**
G_Black	128	1	0	9	22	1	1	3	4	5	35	31	0.89	62.9	11.4
G_Blue	38	1	0	14	27	1	3	4	7	6	48	41	0.85	56.3	14.6
G_Red	70	5	0	30	44	5	11	12	23	1	97	74	0.76	45.4	23.7
Pine Grove	**236**	**7**	**0**	**53**	**93**	**7**	**15**	**19**	**34**	**12**	**180**	**146**	**0.81**	**51.7**	**18.9**
S_Black	966	1	1	3	30	0	2	4	6	9	39	34	0.87	76.9	15.4
S_Blue	734	1	1	0	30	0	1	10	11	4	41	31	0.76	73.2	26.8
S_Red	716	66	18	3	26	48	3	5	8	9	37	47	1.27	70.3	17.0
Warnup	**2416**	**68**	**20**	**6**	**86**	**48**	**6**	**19**	**25**	**22**	**117**	**112**	**0.96**	**73.5**	**21.4**
Total	**3697**	**77**	**22**	**87**	**258**	**55**	**29**	**53**	**82**	**43**	**427**	**367**	**0.86**	**60.4**	**19.2**

Appendix 5: Relative microrelief transects and chenopod floristics

✓ = presence of species within 1m radius sub-quadrats

Site	Dist cm	Elevation cm	M. cheelii	M. excavata	M. pentagona	M. enchylaenoides	M. humillima	M. rohlarchii	Sclerochlamys brachyptera	Sclerolaena diacantha	Comments
Pine Grove	0	-22.0		✓	✓						
Pine Grove	100	-23.0		✓	✓						
Pine Grove	200	-23.5	✓	✓	✓						
Pine Grove	300	-24.5	✓	✓	✓						
Pine Grove	400	-26.0	✓	✓	✓						
Pine Grove	500	-24.0	✓		✓						
Pine Grove	600	-23.0	✓	✓	✓						
Pine Grove	700	-23.0			✓						
Pine Grove	800	-24.0	✓		✓						
Pine Grove	900	-27.0	✓								
Pine Grove	1000	-27.5	✓								Blue replicate
Pine Grove	1100	-28.0	✓								Blue replicate
Pine Grove	1200	-28.5	✓								
Pine Grove	1300	-28.5	✓								
Pine Grove	1400	-28.0	✓								
Pine Grove	1500	-28.5	✓			✓					
Pine Grove	1600	-29.0	✓		✓						
Pine Grove	1700	-30.0	✓		✓	✓					
Pine Grove	1800	-32.0	✓		✓						Gilgai depression
Pine Grove	1900	-33.0									Gilgai depression
Pine Grove	2000	-43.0									Gilgai depression
Budgerum	0	-15.5		✓	✓						Additional 1
Budgerum	100	-16.0		✓							
Budgerum	200	-15.5		✓							
Budgerum	300	-15.5		✓	✓						
Budgerum	400	-16.5		✓							
Budgerum	500	-16.0		✓	✓						
Budgerum	600	-14.5		✓							
Budgerum	700	-15.0									Gilgai depression
Budgerum	800	-17.0									Gilgai depression
Budgerum	900	-14.5									Gilgai depression
Budgerum	1000	-13.0									
Budgerum	1100	-13.0		✓						✓	
Budgerum	1200	-13.5		✓						✓	
Budgerum	1300	-13.0			✓					✓	
Budgerum	1400	-14.5		✓	✓					✓	
Budgerum	1500	-16.5	✓		✓				✓		
Budgerum	1600	-17.0	✓		✓				✓		
Budgerum	1700	-17.0	✓		✓						
Budgerum	1800	-17.5	✓		✓						
Budgerum	1900	-18.0	✓		✓						
Budgerum	2000	-18.0	✓		✓						Red replicate
Warnup	-100	N/A	✓		✓						Red replicate
Warnup	0	-42.0	✓		✓			✓		✓	Red replicate
Warnup	100	-35.5	✓	✓	✓			✓		✓	
Warnup	200	-33.0	✓	✓	✓	✓				✓	
Warnup	300	-35.5	✓	✓	✓			✓		✓	
Warnup	400	-32.0		✓	✓					✓	
Warnup	500	-24.0								✓	
Warnup	600	-22.5								✓	
Warnup	700	-22.5		✓						✓	
Warnup	800	-25.0		✓						✓	
Warnup	900	-28.0		✓		✓					
Warnup	1000	-29.5						✓			
Warnup	1100	-31.5		✓				✓		✓	
Warnup	1200	-35.5	✓	✓	✓			✓			
Warnup	1300	-43.5	✓		✓						
Warnup	1400	-44.0	✓								Black Rep nearby

Warnup	1500	-44.5	✓		✓			Black Rep nearby
Warnup	1600	-38.0	✓	✓	✓			
Warnup	1700	-34.5		✓				Blue Rep on shelf nearby
Warnup	1800	-28.0	✓	✓		✓		
Warnup	1900	-30.5		✓		✓	✓	
Warnup	2000	-32.0		✓		✓		
Warnup	2100	-24.5		✓				

Appendix 6: Relationship between plant size and tuber rings – Raw data

	Site	Region	Date Coll	Tuber Length mm	Tuber Rings No	Tuber Diam mm	Stem Height mm	Stems No	Stem Basal Area mm	Health	Notes
6	McLaughlan	Birchip	3/12/03	15	0.5	2	41	1	1	Vigourous	4 to 6 months old seedling
2	Budgerum	Quambatook	17/09/03	35	4.0	4	32	2	2	Vigourous	Tip missing
1	McLaughlan	Birchip	22/08/03	N/A	5.5	8	55	2	5	Poor	Tuber surface wrinkled
3	Budgerum	Quambatook	17/09/03	64	6.5	10	125	7	5	Vigourous	
4	Pine Grove	Echuca	16/09/03	60	6.5	10	85	12	7	Vigourous	
5	Warnup	Birchip	18/09/03	70	7.5	14	150	21	15	Vigourous	