

# Use of functional traits to identify Australian forage grasses, legumes and shrubs for domestication and use in pastoral areas under a changing climate

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**Abstract.** Considerable uncertainty exists about future climatic predictions but there is little doubt among experts that the future will be warmer. Climate change and the associated elevation in atmospheric CO<sub>2</sub> level and temperatures will provide novel challenges and potential opportunities for cultivated plant species. Plant breeding and domestication can contribute to improvements in both yield and quality of native grasses, legumes and forage shrubs. This review explores the use of functional traits to identify native Australian grasses, legumes and forage shrubs suitable for domestication, to meet the challenges and opportunities under a changing climate in pastoral areas in Australia. The potential of these species in terms of life history, regenerative traits, forage quality and quantity, drought tolerance and invasiveness is examined. The paper focuses on three Australian pastoral regions (high-rainfall temperate south, tropical and subtropical grasslands, low-rainfall semi-arid shrublands), in terms of future climate predictions and potential of selected native species to meet these requirements. Selection for adaptation to new climatic environments is challenging but many native species already possess the traits required to cope with the environment under future climate scenarios.

**Additional keywords:** Australian native grasses, climate change, functional traits, old man saltbush, pastoral areas, plant selection.

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## Introduction

Climate change associated with increases in atmospheric CO<sub>2</sub> and other greenhouse gases will provide novel challenges and potential opportunities for the development of new cultivated plant species (Chapman *et al.* 2012). More than 100 years of plant breeding and domestication in Australia has contributed to improvements in both yield and quality of forage grasses and legumes. Selection and breeding has broadened the climatic adaptation of many species far beyond their original geographic distributions and is continuing. By far the greatest efforts have been invested in introduced forage grasses and legumes from other parts of the world, with relatively little work on the domestication of Australian native species (Whalley 1970; Lodge 1996; Johnston *et al.* 1999; Whalley *et al.* 2005). However, researchers and producers have realised that certain native species that are adapted to local soil and climatic conditions are perhaps more resilient to climatic extremes and poor soils (phosphorus (P)-deficient, acidic sandy and saline) and can still provide good seasonal productivity (Jefferson *et al.* 2002) or nutrients for livestock at

a time when these are limiting (Masters *et al.* 2007; Pearce *et al.* 2010; Revell *et al.* 2013).

Australia is the world's driest inhabited continent, with half of its total land area receiving <300 mm annual average rainfall. In addition, rainfall is notoriously unreliable and Australian plants and animals are well adapted to a system where water availability is often a stronger driver of ecosystem activity than daylength or temperature (Robin 2007). Prior to European settlement, there was no history of cultivation, and grazing was by macropods (such as kangaroos and wallabies) rather than ruminants. Australian soils are relatively old and weathered, and in many cases low in fertility (Wadham and Wood 1950). Australia's recent geological history is such that no mass extinctions of flora species occurred during the Pleistocene glaciations, such as those that happened in the northern hemisphere (Mithen 2003). This lack of mass extinctions and the following rapid revegetation has had important implications for the breeding systems of the present indigenous herbaceous flora and the adaptation of individual species to a variable climate (Groves and Whalley 2002; Robin 2007; Whalley *et al.* 2013).

In addition to these unusual historical characteristics, the latitudinal range of Australia extends from the tropics to the temperate regions, which are expected to have different changes to their future climates. Therefore, native species adapted to a wide range of climatic conditions are available for domestication.

Grasses, legumes and forage shrubs contribute substantial value via ruminant production for meat, dairy, wool and other products. In Australia, commodities that result from pasture production have been valued at AU\$9.3 billion (ABARES 2011). These species also contribute a 'difficult-to-measure' value in providing ecosystem services, including increased water use, thus correcting hydrological imbalances associated with annual cropping systems (Farrington *et al.* 1992; Barrett-Lennard 2002), improving soil stability (Le Houérou 1992), and providing habitat for native animals (Lancaster *et al.* 2012) and amenity species in facilities such as sports grounds and golf courses as well as in residential gardens (Chapman *et al.* 2012).

#### *Native forage species seed industry*

The native forage seed industry has been slow to develop in Australia. Although several suppliers list seeds of native grasses in sufficient volumes for pastoral use, the commercial supplies of seed of native legumes and forage shrubs are generally limited to small packets. In all cases, the prices are substantially higher than those for introduced pasture species.

Seed from native forage shrubs tends to be harvested by hand, and shaking the shrubs is often sufficient to dislodge seed into collection containers. The majority of seed originates from 'wild' populations that are sampled by licenced seed collectors. In addition, *Atriplex* L. and *Maireana* Moq. seed may be collected from nurseries or on-farm plantations. Given the small size of seeds, small numbers of plants established per ha and ease of harvest, manual seed collection from chenopods is not as critical a barrier to adoption as it is for perennial legumes and grasses.

#### *Domestication of native species*

Agriculturalists have propagated preferred forms and culled undesirable types of many plant species to produce each subsequent generation since the dawn of civilisation. This process has been deemed 'domestication' and it is an evolutionary process operating under the influence of human activities (Harlan 1975). Since it is evolutionary, the progression from the wild state to a domesticated form that is different from its progenitors is slow and gradual (Harlan 1975), but the use of modern techniques can speed it up (Van Tassel and DeHaan 2013). Domesticated plant species often differ from their wild relatives in anticipated or predictable ways. Key aspects of a plant species' functional traits, how the species interacts with its environment and with other species, have been used to tame it. These traits may include characteristics such as selecting for increased size of reproductive organs, reduced physical and chemical defences or changes in biomass allocation (more in fruits, roots or stems, depending on human needs). Therefore, our challenge is to select new forage plants that meet the exigencies of climate change.

This review examines the use of functional traits to identify native Australian grasses, legumes and forage shrubs suitable for domestication to meet the challenges and opportunities under

a changing climate in pastoral areas. Functional traits are any morphological, physiological or phenological features, measurable for individual plants at the cell to the whole organism level, which potentially affect their fitness in particular environments (Pérez-Harguindeguy *et al.* 2013). For the purposes of this review, the pastoral areas in Australia will be dealt with in three broad climatic zones: the high-rainfall temperate south, the tropical and subtropical grasslands in the north, and Mediterranean or low-rainfall semi-arid shrublands.

#### **Likely future climate changes**

Uncertainty about future climate predictions is high; however, there is little doubt among experts that the future will be warmer. Average temperatures are projected to rise by 0.6–1.5°C by 2030 and 1.0–5.0°C by 2070 when compared with the climate of recent decades, with an increase in the frequency, intensity and duration of extreme heat events (Hennessy *et al.* 2007; CSIRO and BoM 2012). Therefore, the effects of these higher temperatures on the forage base are the most certain impacts. Effects on rainfall are more speculative (Henry *et al.* 2012) and more localised, but they certainly involve greater variability and a greater incursion of summer rainfall into southern parts of Australia. The northern parts of Australia are generally expected to be slightly dryer with increased variability of rainfall (Henry *et al.* 2012).

These changes are likely to occur very rapidly on a geological timescale, and as a result, there will be little time for natural plant populations to either evolve or migrate to cope with the new conditions. Therefore, the introduction of domesticated or semi-domesticated native forage species into new areas would be a useful strategy. This process would be a form of grassland restoration introducing forage species or varieties not native to the new areas. Many restoration guidelines strongly recommend the use of local sources of seed in native plant revegetation projects because of an assumed local adaptational advantage and lower risk of unwanted genetic effects (Jones *et al.* 2001; Volis *et al.* 2002; Potts *et al.* 2003; Lenssen *et al.* 2004; Capelle and Neema 2005; McKay *et al.* 2005; O'Brien *et al.* 2007; Byrne *et al.* 2011). Whalley *et al.* (2013) have argued that these assumptions do not apply to Australian native grasses because of their evolutionary history, flexible breeding systems and relatively short population turnover times. The same principles may well apply with native legumes and forage shrubs.

#### **Functional traits of forage species**

Forty-three different functional traits were defined by Pérez-Harguindeguy *et al.* (2013), and some of those and other traits that are relevant for the effects of climate change on forage species are described below.

##### *Life history traits*

Life history attributes including plant lifespan (annual, perennial) and plant phenology, especially flowering time and extent, probably have the greatest impact on grassland production and forage quality (Humphreys *et al.* 2006).

##### *Regenerative traits*

These include the mode of dispersal, size, shape and mass of the propagule (seed, fruit) (Pérez-Harguindeguy *et al.* 2013) and, for

the domestication of native forage species, can be dealt with under several headings.

#### *Timing of seed production*

Species with determinate flowering produce one seed crop per year at the one time, depending on the seasonal conditions, and the timing of the seed harvest does not present a problem (Waters *et al.* 2000; Cole and Johnston 2006). However, species with indeterminate flowering produce seed over an extended period, depending on the rainfall distribution during their growing season.

#### *Seed shattering*

Most native species shed their seed as it ripens, and so a large part of the seed crop may be lost because it ripens over an extended period. Part of the domestication process involves the selection of lines possessing mechanisms for seed retention. In many species, particularly grasses, abscission layers form at the base of the florets or spikelets, and usually only one or two genes are involved. The identification of these abscission genes and the search for alleles for seed retention is therefore important (e.g. for *Microlaena stipoides* (Labill.) R.Br.; Malory *et al.* 2011). Other mechanisms for seed retention can be useful for some species; for instance, Indian ricegrass (*Oryzopsis hymenoides* (Roem. and Schult.) Ricker) has single florets inside two large glumes. As the seed ripens, these glumes gape widely and the individual seeds fall out. Measurement of the glume angles of several populations identified some in which the glume angle was smaller and the mature seeds were retained within the glumes, allowing better harvesting of the seed (Whalley *et al.* 1990). Similar mechanisms may be present in some native Australian grasses.

#### *Seed harvesting*

Mechanical harvesting of the seeds of native forage species (grasses, shrubs and legumes) presents a challenge for growers, particularly as the seeds are often borne in the vegetative parts and not exposed above rest of the plant, as with cereal crops. One approach is to select material for domestication in which the seeds are borne above the vegetative parts of the plant, making harvesting easier (Van Tassel and DeHaan 2013). In addition, there is a wide range of seed appendages (Peart 1984) involved in seed dispersal but they make seed harvesting difficult. Various types of brush and vacuum harvesters have been constructed (Waters *et al.* 2000; Cole and Johnston 2006) and the harvested material usually contains a large quantity of trash.

#### *Seed cleaning*

Cleaning of the seed is often difficult and the seeds of some species are very fragile and easily damaged by harvesting and cleaning equipment (e.g. *Microlaena stipoides*; Waters *et al.* 2000). Cleaning of the seed of some species (e.g. *Themeda triandra* Forssk. (syn. *T. australis* (R.Br.) Stapf) is so difficult that special machinery has been designed for this purpose (Waters *et al.* 2000; Cole and Johnston 2006). Modifications of seed appendages are important aspects of forage plant domestication. Cleaning propagules of native species to naked seeds will make them easier to sow through conventional sowing equipment but usually reduces the shelf-life of the seed. It also often results in

reduced establishment success (Lodge and Whalley 1981; Waters *et al.* 2000).

#### *Seed dormancy*

Primary dormancy is a feature of the seeds of many naturally occurring species, and these mechanisms prevent the germination of the whole crop after shedding from the parent plant (Lodge and Whalley 1981; Finch-Savage and Leubner-Metzger 2006). Usually, the dormancy gradually breaks down during a period of after-ripening so that some seeds germinate whenever rain falls. On the other hand, the dormancy breaking of some annual species is very precise so that a population of seeds are ready to germinate at the correct time when the season breaks (Norman *et al.* 1998). Seed dormancy mechanisms are often very complex and the process of domestication may involve selection to modify these mechanisms. On the other hand, certain dormancy mechanisms may be an advantage, depending on the use to which the harvested seed of the domesticated species will be put. For example, a cultivar of bladder clover (*Trifolium spumosum* L.) has been selected for higher long-term dormancy and therefore seedbank persistence during longer cropping rotations (Loi *et al.* 2012). Dormancy often resides in the ancillary structures surrounding the seeds and so can be broken simply by seed cleaning, provided this can be done without damaging the seed itself.

#### *Temperature and seed germination*

The temperature requirements for seed germination of C<sub>4</sub> species are generally higher than those of C<sub>3</sub> species, and to some extent, these requirements govern the time of the year when sowings of these species are most likely to be successful (Lodge 1981; Lodge and Whalley 1981, 2002). Many native species have other specific requirements such as heat or other treatments (Langkamp 1987), darkness (*Spinifex sericeus* R.Br., Maze and Whalley 1992) or smoke water (Dixon *et al.* 1995). These requirements can make domestication difficult for some species.

#### *Seed sowing*

Seeds of many native species have ancillary attachments associated with seed dispersal, ensuring that the seed lands on the soil surface with a specific orientation, and/or important in seed germination (Beadle 1952; Peart 1984; Paterson 2011). These ancillary attachments often mean that the seed will not flow readily through conventional sowing equipment (Chivers and Raulings 2009). If the ancillary structures are removed mechanically, the seed dormancy mechanisms are often affected (e.g. *Rytidosperma* Steud. spp.) and the longevity is reduced, or the seed is damaged during the process (e.g. *Microlaena stipoides*) (Lodge and Whalley 1981; Whalley 1987; Waters *et al.* 2000). An alternative is seed pelleting so that the seed will run through conventional seeding equipment (Chivers and Raulings 2009). The domestication process may involve selecting for changes in these ancillary structures.

#### *Seedling establishment*

A feature of many Australian native forage species (particularly grasses) is that the seeds germinate readily, but once the seedlings emerge, they are likely to be relatively

slow-growing for several months (Barrett-Lennard *et al.* 1991; Waters *et al.* 2000; Chivers and Raulings 2009). The result is that they are susceptible to weed competition, and so weed management, both before and after sowing, is often critical for success, as is the management of the newly emerged stand (Semple *et al.* 1999). Seedling vigour can therefore be an important trait that requires modification during domestication (Whalley *et al.* 1966a, 1966b; McWilliam *et al.* 1970).

#### *Forage quantity and quality*

In general, C<sub>4</sub> grasses have a higher fibre and lower protein content of their leaves and, consequently, a lower digestibility than C<sub>3</sub> grasses (Lodge and Whalley 1983; Archer and Robinson 1988). Therefore, climate changes that result in changes to pasture composition from C<sub>3</sub> to C<sub>4</sub> grasses will have an impact on the forage value of the grasses involved. Many of the native forage shrubs of the family Chenopodiaceae are C<sub>4</sub> plants with moderate digestibility, and domestication will involve selection to improve forage quality (Norman *et al.* 2010a).

#### *Drought tolerance*

Drought and more extreme temperature events are two of the most significant features of future climate projections. The mechanisms of adaptation to water deficits can be divided into the following categories (Kramer 1980; Levitt 1980; Lazarides 1992; Turner 1996), with one or more of these mechanisms operating in some species to ensure their survival in a variable climate.

##### *Desiccation tolerance*

A rare group of plants can desiccate to air dryness for long periods, but revive rapidly upon re-watering. This group of plants that are truly desiccation-tolerant are termed resurrection or poikilohydric plants (Lazarides 1992; Scott 2000).

##### *Drought escape*

Some plant escape droughts by completing their life cycles before serious soil and plant water deficits develop; for example, annuals survive dry periods as seeds.

##### *Drought tolerance with low plant water potential*

This is the ability of a plant to endure periods without significant rainfall and endure low tissue water status, i.e. dehydration tolerance (Sinclair and Ludlow 1986).

##### *Drought tolerance with high plant water potential*

This is the ability of a plant to endure periods without significant rainfall while maintaining a high plant water status, i.e. dehydration postponement (Sinclair and Ludlow 1986). It can be achieved by either morphological or physiological modifications that reduce transpiration or increase absorption.

##### *Drought dormancy*

Drought dormancy is a feature of many perennial native grasses, in that the aboveground parts of the plants senesce stimulated by low soil water status (Whalley and Davidson 1969; Harradine and Whalley 1978). In Australian native

grasses, this dormancy typically occurs during summer, but drought dormancy can occur in any season. Plants recommence growth when seasonal conditions become favourable, in terms of both temperature and soil water.

#### *Resprouting capacity after disturbance*

This is the capacity of a plant species to resprout after destruction of its aboveground biomass (Pérez-Harguindeguy *et al.* 2013). This disturbance includes grazing, browsing by herbivores, extreme drought, frost events and fire.

#### *Dry matter production*

Tiller density, leafiness, crown diameter, and regrowth after harvest and grazing are important traits of forage species. Rising atmospheric CO<sub>2</sub> levels, increasing temperatures and changing rainfall regimes will alter pasture production (Crimp *et al.* 2010), including the relative production of C<sub>3</sub> and C<sub>4</sub> species. Changes in rainfall distribution and evaporation will have impacts on pasture production and perennial plant persistence.

#### *Adventive ability and weediness*

An adventive species is one that has arrived in a specific geographic area from a different region but its population is not self-sustaining (Wagner *et al.* 1999). Population numbers are only increased through re-introduction. Many native grasses and legumes that have disappeared through the introduction of introduced pasture species now behave as adventive species. Domestication or perhaps grazing management (FitzGerald and Lodge 1997) would need to make them more invasive so that populations can be managed to become self-sustaining.

Seedling establishment of native forage species is generally not easy, and the invasiveness of many of these species (grasses, shrubs and legumes) is generally considered low (Barrett-Lennard *et al.* 1991; Waters *et al.* 2000; Chivers and Raulings 2009). In a widespread trial of different lines of both native and introduced perennial grasses across five states in southern Australia, seedlings were raised in tube stock and planted into holes in weed matting to ensure that results were not biased in favour of those species with the greatest invasiveness (Whalley *et al.* 2005). The seed production and subsequent seedling establishment after the parent plants were established and the weed matting had been removed differed widely among species, lines and locations of the trials (Waters *et al.* 2005). It is clear that the post-emergent management is critical in ensuring that sown native species become important components of the resultant pasture, and grazing animals are important aspects of this management. Grazing management and other techniques such as scalping can dramatically influence the invasiveness of individual species, and these can be used to increase the abundance of desirable species, as well as discouraging the invasion of undesirable species (Gibson-Roy *et al.* 2007a, 2007b; Firm *et al.* 2013).

A universal characteristic of weedy species is that they have the ability to invade plant communities where they are not wanted. For instance, buffel grass (*Cenchrus ciliaris* L.) is invasive in national parks and other public lands in Australia and in parts of America, but is of great value to the livestock industries over large



areas of semi-arid and arid Australia (Eyre *et al.* 2009; Miller *et al.* 2010). It is one of 20 plant species originally listed as 'Weeds of National Significance' in Australia (Thorpe and Lynch 2000).

### Forage legumes

Native herbaceous legumes originally occurred throughout the grasslands and grassy woodlands of Australia. However, with the introduction of sown pastures and cropping, they have largely disappeared from the higher rainfall parts of the country, except for areas that have been retained as predominantly native pastures or in reserved areas. Most are perennials with occasional biennials and very few annual species, and their growth habits range from prostrate, twining to upright (Cocks 2001). Many of them have their major growth period in the warm season, even in southern parts of the continent, whereas others behave as yearlong green species (Lunt *et al.* 1998; Cocks 2001). All legumes are C<sub>3</sub> species.

Australian soils are generally low in P and nitrogen (N) (Wadham and Wood 1950; Williams and Andrew 1970); the use of superphosphate and Mediterranean clovers and medics commenced in the 1920s, followed by the introduction of Townsville stylo (*Stylosanthes humilis* H.B.K.) in northern Australia (Williams and Andrew 1970). As a result, suitable introduced herbaceous legumes are widespread in sown pastures or those that have been heavily topdressed with superphosphate, throughout the higher rainfall parts of the country (including the wet tropics). However, suitable herbaceous legumes are needed as pasture components in lower rainfall regions and for those parts of the country likely to become hotter and dryer in the future. The symbiotic root nodule bacteria for introduced legume species are widespread within these parts of the country (Brockwell and Hely 1966; Khu 1969). The domestication of some of the native herbaceous legumes may fill this need.

Early comparisons with introduced legumes occurred on soils with relatively low P levels (Millington 1958; Britten *et al.* 1979; Cohen and Wilson 1981), and the results of this early work showed that some ecotypes of the species tested gave yields similar to, or even better than, *Medicago sativa* L. or other introduced perennial legumes and were comparable in terms of digestibility, protein and P content.

Denton *et al.* (2006) found that the root distributions of *Kennedia prorepens* F. Muell., *Lotus australis* Andrews and *M. sativa* were all different when grown in pots with three different levels and distributions of P in the soil. When there was a high level of added P in the top 50 mm of soil, the majority of the roots of *M. sativa* were in this region, whereas root distribution of *L. australis* was relatively unaffected compared with the distribution in the controls in which no P was added (Denton *et al.* 2006). The response of *K. prorepens* was intermediate between that of the other two species. The third treatment involved adding an intermediate level of P to the top 500 mm of the soil, and the effects on the root distribution of *K. prorepens* and *M. sativa* were intermediate between the control and the high P level added to the surface soil. The levels of mono-ester phosphatases in 1-mm slices of soil adjacent to the roots were also examined, and the addition of P to the soil reduced their activity only for *K. prorepens*. Millington (1958)

found that the roots of another species of *Kennedia* (*K. prostrata* R.Br.) grew to ~2 m, compared with ~30 cm for subterranean clover (*Trifolium subterraneum*), east of Perth in Western Australia. The root distributions of at least some of the native legumes appear to enhance the acquisition of P from low-phosphate soils.

Several programs of domestication were commenced during the 1970s and 1980s (Gutteridge and Whiteman 1975) but none resulted in varieties that were registered under Plant Breeders Rights or that became commercially available. *Glycine latifolia* (Benth.) C.A. Newell and Hymowitz was selected in Queensland and was nearly ready for Plant Breeders Rights registration in 1996, but the project was abandoned because of seed production problems (R. M. Jones, 1996, pers. comm.). A related species, *Glycine tabacina* (Labill.) Benth., was considered for domestication within the high-rainfall temperate south region (Heard 1996). This species is a warm-season perennial that makes little growth in the winter, but occurs naturally in the higher rainfall parts of New South Wales and Victoria (Harden 1991). Cool-season legumes are generally readily available in this region but perhaps a warm-season perennial would be of value if climate change results in the more southern excursion of summer rainfall events. Several lines were selected over the years as potential candidates for domestication, but generally, difficulties were experienced with commercial seed production.

There is renewed interest in the domestication of native legumes for forage purposes as well as potential grain crops (Dear *et al.* 2008; Hughes *et al.* 2008; Ryan *et al.* 2008; Bell *et al.* 2010, 2012). We will deal only with the forage species in this review. In addition, there is renewed interest in the methodology of the procedures used in selecting species and accessions for field evaluation (Snowball *et al.* 2010). There are several genera of native herbaceous perennial legumes, including *Swainsona* Salisb., *Glycine* L., *Cullen* Medik. (syn. *Psoralea* L.), *Lotus* L. and *Kennedia* Vent., but none have been successfully developed as a cultivated plant (Dear *et al.* 2007). Within this group, *Cullen australasicum* (Schltdl.) J.W. Grimes is of interest and its advantage over *M. sativa* is its greater drought tolerance (Bennett *et al.* 2011; Real *et al.* 2011; Bennett *et al.* 2012; Humphries *et al.* 2014). This species occurs naturally over widespread areas of south-western New South Wales, South Australia and the southern part of the Northern Territory (Humphries *et al.* 2014). On the basis of these studies, we have selected eight species that the literature suggests would be the best candidates for domestication (Table 1).

Many species of native legumes contain toxic elements that render them unsuitable for grazing (Cocks 2001), and those best known among the grazing industry are species of *Swainsona* commonly called the Darling peas. There are ~85 species in Australia (McKenzie 2012) and they occur right across the country, but the records are sparser in the driest parts and in the tropical north (AVH 2014). The active principle is swainsonine and/or calystegine, the onset is delayed or has chronic effects, and there is no effective therapy once animals display severe symptoms (McKenzie 2012). The concentration of the active principles varies among species, and they have been isolated from *Swainsona colutooides* F. Muell., but field symptoms have not been reported. Cyanogenetic glycosides are common in

**Table 1. Functional traits of Australian native forage legumes that make them suitable for use in a changing climate (traits followed by ‘a’) and that need to be altered during the selection process leading to domestication (traits followed by ‘b’)**

Sources of the information are indicated by the superscripts; where there are no superscripts, the information is based on the authors’ experience

Functional trait	Attributes	<i>Cullen australasicum</i> (Schltld.) J.W.Grimes	<i>Glycine latifolia</i> (Benth.) Newell and Hymowitz	<i>Glycine tabacina</i> (Labill.) Benth.	<i>Kennedia prorepens</i> F.Muell.	<i>Lotus australis</i> Andrews	<i>Rhynchosia minima</i> (L.) DC.	<i>Swainsona colutooides</i> F.Muell.	<i>Trigonella suavissima</i> Lindl.
<b>Cultivars/Selections</b>									
<b>Recruiter</b>									
Life History	Perennial (P) biennial (B) annual (A)	P (a) <sup>K</sup>	P (a)	P (a)	P (a) <sup>K</sup>	P (a)	P (a) <sup>K</sup>	A/B (a) <sup>F</sup>	A (a) <sup>K</sup>
Regenerative traits	Flowering: determinate (D) indeterminate (I)	I (b) <sup>C</sup>	I (b) <sup>B</sup>	I (b)	I (b)	I (b)	D (a) <sup>I</sup>	D (a) <sup>I</sup>	D (a)
	Seed production (kg ha <sup>-1</sup> )	~1000 <sup>C</sup>	?	?	?	?	?	?	?
Seed (pod) retention: Low (L) moderate (M) High (H)	Seed appendages: yes (Y) no (N)	H/M (a,b) <sup>C,I</sup>	M (b) <sup>B</sup>	M (b) <sup>A</sup>	L (b) <sup>F</sup>	L (b) <sup>F</sup>	L (b)	M-H (b) <sup>F</sup>	L (b) <sup>I</sup>
	Seed cleaning: need special equipment: yes (Y) no (N)	N (a) <sup>C</sup>	N (a) <sup>B</sup>	N (a) <sup>A</sup>	N (a)	N (a)	N (a)	N (a)	N (a)
	Primary dormancy: deep (P) non-deep (A)	N (a) <sup>C</sup>	N (a) <sup>B</sup>	N (a) <sup>A</sup>	N (a)	N (a)	N (a)	N (a)	N (a)
	Germination, special requirements: yes (Y) no (N)	A (a) <sup>C</sup>	A (a) <sup>B</sup>	A (a) <sup>A</sup>	A (a)	A (a)	A (a)	A (a)	A (a)
Seed sowing, special equipment required: yes (Y) no (N)	Seed sowing, special equipment required: yes (Y) no (N)	N (a) <sup>C</sup>	Y (a) <sup>B</sup>	Y (a) <sup>A</sup>	Y (a)	Y (a)	Y (a)	?	?
	Seedling establishment, susceptible to weed competition: yes (Y) somewhat (S) no (N)	N (a) <sup>C</sup>	N (a) <sup>B</sup>	N (a) <sup>A</sup>	N (a)	N (a)	N (a)	N (a)	N (a)
Growth habit	Upright (U), Prostrate (P), Twinning (T)	N (a) <sup>C</sup>	Y (b) <sup>B</sup>	Y (b) <sup>A</sup>	S (b) <sup>E</sup>	N (a) <sup>E</sup>	N (a)	N (a) <sup>E</sup>	?
	Annual forage production under good conditions (kg ha <sup>-1</sup> )	U (a) <sup>E</sup>	T (a) <sup>M</sup>	T (a) <sup>E</sup>	P (a) <sup>E</sup>	U (a) <sup>E</sup>	U (a) <sup>E</sup>	U (a) <sup>E</sup>	?
	Digestibility (%)	400–1200 <sup>C</sup>	330–711 <sup>B</sup>	31–140 <sup>A</sup>	?	?	?	?	High?
Drought tolerance	Crude protein (%)	81–86 <sup>D</sup>	?	60–65 <sup>A,L</sup>	55 <sup>J</sup>	72 <sup>J</sup>	High?	75 <sup>J</sup>	High?
	high (H) moderate (M) low (L)	16–21 <sup>D</sup>	?	12–16 <sup>A</sup>	12 <sup>J</sup>	23 <sup>J</sup>	High?	23 <sup>J</sup>	High?
Invasiveness or weediness	high (H) moderate (M) low (L)	H (a) <sup>C</sup>	H (a) <sup>B</sup>	M (a) <sup>A</sup>	H (a)	H (a)	H (a)	H (a)	L (a)
	high (H) moderate (M) low (L)	L (a)	L (a) <sup>B</sup>	L (a) <sup>A</sup>	L (a)	L (a)	L (a)	L (a)	L (a)
Plant secondary compounds	Furanocoumarins <sup>H,K</sup>	L (a)	L (a)	L (a)	L (a)	L (a)	L (a)	L (a)	L (a)
	Cyanogenetic glycosides <sup>G,H</sup>	?	?	?	?	?	?	?	?
Plant secondary compounds	Swainsonine <sup>H</sup>	?	?	?	?	?	?	?	?
	Coumarins <sup>I</sup>	?	?	?	?	?	?	?	?

<sup>A</sup>Heard (1996). <sup>B</sup>Rees et al. (1993). <sup>C</sup>Humphries et al. (2014). <sup>D</sup>Bennett et al. (2012). <sup>E</sup>Ryan et al. (2008). <sup>F</sup>Bell et al. (2011). <sup>G</sup>Real et al. (2005). <sup>H</sup>McKenzie (2012). <sup>I</sup>Bell et al. (2012). <sup>J</sup>Robinson et al. (2007). <sup>K</sup>Ryan et al. (2011). <sup>L</sup>Cohen and Wilson (1981). <sup>M</sup>Millington (1958).

plants, and when hydrolysed, they produce cyanide (HCN), resulting in acute poisoning. This can be controlled by the administration of sodium thiosulfate if detected early enough (McKenzie 2012). *Lotus australis* is widespread throughout Australia and active breeding programs are in place to select for low levels of glycoside (Real *et al.* 2005; Dear and Ewing 2008; Ryan *et al.* 2008). The third group of native legumes with potential for domestication but of concern because of possible poisons are the 16 species of *Cullen*. These occur throughout Australia but are sparser in the south-west of the continent (Bennett *et al.* 2012; AVH 2014). The active principles in these species are furanocoumarins, which can cause photosensitisation in horses with delayed onset or chronic effects. There is no specific therapy once symptoms appear (McKenzie 2012). The species of interest is *C. australasicum*, which is not listed by McKenzie (2012) as causing problems with horses. Several other species of native legumes are reported by McKenzie (2012) as containing substances poisonous to domestic livestock but they have not been under active consideration recently as potential species for domestication.

The only member of the tribe Trifolieae native to Australia is the cool season annual species *Trigonella suavissima* Lindl. This species is confined to floodplains in south-western Queensland, the northern part of the Murray–Darling system and parts of Western Australia (Brockwell 1971; Brockwell *et al.* 2010). This species germinates after good rains in low-lying areas during winter–spring and is particularly abundant after cool-season floods. Under these conditions, it produces abundant high-quality feed, particularly for cattle (Cunningham *et al.* 1981). As far as we are aware, no efforts have been made in Australia to domesticate this species but it would be valuable if it could be sown, together with its symbiont (Brockwell 1971; Brockwell *et al.* 2010), in flood-prone areas further south in the future.

### High-rainfall temperate south

The matrix species (Grubb 1986) of the herbaceous component of the original vegetation of this part of Australia at the time of European settlement were warm-season ( $C_4$ ) and yearlong green perennial grasses ( $C_3$ ). The interstitial species were annual and perennial dicots with a warm-season perennial component as well as a few annual grasses (Moore 1970; Lunt *et al.* 1998). Grazing and the addition of superphosphate plus seeding with subterranean clover (*Trifolium subterraneum* L.) and appropriate grasses have seen the demise of the native perennial grasses and the associated interstitial species, and the pastures became dominated by annual introduced grasses and legumes (Moore 1970; Blair 1997).

These cool-season ( $C_3$  species) annual pastures thus became common in the higher rainfall parts of southern Australia where the rainfall is winter-dominant (Dear and Ewing 2008). In these pastures, both the grass and legume components germinate with the opening rains in autumn. At the end of the growing season in late spring–early summer, both components flower, set seed and die, and the livestock depend on dry feed during the summer supplemented by the high protein of the subterranean clover seed, which the livestock (particularly sheep) can access from on or just below the soil surface (Rossiter 1966). When landscapes depend on annual grasses as well annual legumes, they are prone

to the development of soil acidity, and a more sustainable system is to combine introduced perennial grasses with the annual legumes (Williams 1980; Blair 1997; FitzGerald and Lodge 1997). The establishment and maintenance of introduced perennial pasture grasses in these pastures requires careful management (FitzGerald and Lodge 1997). Most of these introduced  $C_3$  perennial grasses exhibit determinate flowering in the spring followed by summer dormancy (Volaire and Norton 2006), and therefore have limited capacity to respond to the projected increasing incursions of summer rainfall events into this region.

Drought and more extreme temperature events, increased atmospheric  $CO_2$  levels, as well as greater incursions of summer rainfall are the most significant features of future climate projections. Extreme temperature events (severe frost or heat waves) can be devastating for introduced perennial pasture grasses, especially if they do not have reserve capacity for growth (e.g. underground storage organs) (Chapman *et al.* 2012). In addition, the rising temperatures could result in a shorter growing season when soil water is available in the autumn–spring period and a reduction in frost damage (Stokes *et al.* 2010). The increased likelihood of summer storms means that dry feed will be reduced in value in winter annual pastures.

Rising atmospheric  $CO_2$  levels, increasing temperature, and changing rainfall regimes will alter pasture production (Crimp *et al.* 2010). Rainfall distribution and evaporation will have an impact on pasture production and perennial plant persistence. Cullen *et al.* (2009) predicted a 22–37% increase in dry-matter production of temperate-grass-dominated pastures in southern Australia, stimulated by raising the atmospheric  $CO_2$  from 380 to 550 ppm. In addition to this, the rising temperatures could result in a longer growing season and a reduction in frost damage (Stokes *et al.* 2010). However, this increased plant growth in the cooler months could deplete the soil moisture at the expense of subsequent pasture in the spring (Stokes *et al.* 2010).

Animal production from annual cool-season pastures in this region is particularly susceptible to the projected climate changes in the future. The critical functional traits that make these species risky are their annual growth pattern, tied to particular temperature, daylength and available soil-water conditions for their autumn establishment; their growth confined to the winter and spring period; and finally the susceptibility of senesced material to a reduction in feeding value after rain during the summer months.

On the other hand, many native perennial grass and legume species have indeterminate flowering and growth and, once established, provided soil water is available, have the capability for forage production during both winter and summer ( $C_3$  species) or during the summer for  $C_4$  species, depending on their degree of vegetative summer dormancy (McWilliam 1978; Volaire and Norton 2006; Crimp *et al.* 2010). Those native perennial  $C_3$  grasses that have indeterminate flowering have been called yearlong green perennials (Lodge and Whalley 1989).

Many perennial native forage species, both grasses and legumes, have substantial drought tolerance, perhaps because of their evolutionary history. The different strategies for coping with drought stress have been described above.

These desirable functional traits of native forage species, both grasses and legumes, suggest that they would be valuable species

to incorporate into pastures in this region to cope with climate changes in the future. However, other functional traits need to be changed during domestication without the loss of the valuable characteristics described above (Tables 2, 3).

#### *Functional traits that need changes*

##### *Seed production, seed shattering, seed harvesting and cleaning*

By far the majority of the perennial native grasses and legumes that are suitable for domestication for this region have indeterminate flowering, which means that they do not have summer dormancy (Volaire and Norton 2006) and therefore do have the capacity to respond to summer rainfall when it occurs (Waters *et al.* 2000; Cole and Johnston 2006). Consequently, the indeterminate flowering of species suitable for this region is a trait that should be retained. On the other hand, seed shattering is almost universal among the species suitable for this region, and so it is an important trait to be eliminated during the domestication process (e.g. for *Microlaena stipoides*; Malory *et al.* 2011).

The selection of lines of different species where the inflorescences are produced above the leafy parts of the plants is probably less important than selection for seed retention. The ingenuity of the seed growers that has resulted in the production of mechanical harvesting equipment is impressive. Various types of brush and vacuum harvesters have been constructed (Waters *et al.* 2000; Cole and Johnston 2006), and the harvested material usually contains a large quantity of trash. Further drying and cleaning of the seed is then necessary but does not present insuperable difficulties. For shrub species where ideal planting densities are 700–1000 plants ha<sup>-1</sup>, few seeds are required, so the importance of mechanical harvesting is reduced.

##### *Seed dormancy, seed germination and seed sowing*

Seed dormancy is generally not a problem with the species currently under consideration for domestication for this region, except perhaps for *Themeda triandra* (Groves *et al.* 1982; Cox 2012).

The ancillary structures of many native seeds are so clearly associated with seed dispersal and ensuring that the seed lands on the soil surface with a specific orientation (Peart 1984) that the deliberate selection against such characteristics could be dangerous. Perhaps an alternative approach is seed pelleting so that the seed will run through conventional seeding equipment (Chivers and Raulings 2009).

##### *Seedling establishment*

The slow growth of the seedlings appears ubiquitous among native Australian forage species. Perhaps this trait is linked to others that would be valuable for future climates. Therefore, we suggest that the selection for fast-growing seedlings could be counter-productive and a more useful approach in the short term would be better weed management, both before and after sowing, and better management of the newly emerged stand. Equally, insect control is critical for slow growing seedlings.

### **Tropical and subtropical grasslands**

This region extends across the north of Australia inland from the coastal ranges, extending as far south as the inland slopes of

northern New South Wales (Williams *et al.* 2002). The climate is warm although winters are mostly cool towards the south, with summer-dominant rainfall distribution. The soils are variable, and cracking clay soils are extensive throughout the region (Williams *et al.* 2002). Pastures in these areas are dominated by perennial grasses (virtually all C<sub>4</sub> species) and legumes, which form the matrix species of the grasslands (Grubb 1986; Tothill and Gillies 1992). These species respond rapidly to the start of the wet season in spring–early summer and remain dormant during the dry season (winter). The interstitial species are mostly annuals or short-lived perennials, which have similar annual growth patterns, germinating with the opening rains and seeding and dying at the end of the wet season. In general, the native eucalypt forests and woodlands in these areas have been extensively cleared and replaced by pastures comprising introduced grasses and legumes that are predominantly used for intensive livestock grazing of cattle, with some sheep in the south-eastern part of the region (Williams *et al.* 2002). However, in dryer parts of the tropics, the emphasis changes to the dominance of native species in both the matrix and interstitial species (Tothill and Gillies 1992). It is a feature of the perennial plants of these pastures that when winter rainfall does occur, the perennials can respond to the unseasonal soil moisture availability.

The ‘best-bet’ climate predictions for 2070 under the high-emissions scenario suggests hotter (2.5–5°C) and drier (–20% to –5%) conditions (CSIRO and BoM 2012), although some of the projected changes in rainfall appear small compared with the year-to-year variability (McKeon *et al.* 2009). The negative effects of the declines in rainfall and increasing incidence of drought on pasture productivity may initially be offset by the benefits of higher CO<sub>2</sub> and a prolonged growing season from warming (Stokes and Howden 2010). More intense rainfall may increase the risk of erosion and lead to declines in pasture quality (Stokes and Howden 2010). Climate change is likely to further stress many grazing enterprises in the dryer parts of this region that are already marginally viable and have few opportunities for adaptation (Stokes and Howden 2010). The predicted increases in temperatures will have an impact on livestock, particularly water requirements and distances to watering points (Stokes *et al.* 2010).

Within Queensland, there is demand for seed of certain native grasses for sowing into degraded grazing lands. To date, most seed has been harvested from natural stands. This has led to inconsistent supply, expensive seed and, often, low sowing quality (few viable caryopses per unit weight). Recent project work has focused on the domestication of a range of native grasses for use in the tropical pastures: black spear grass (*Heteropogon contortus* (L.) P.Beauv. ex Roem. and Schult.), Queensland blue grass (*Dichanthium sericeum* (R.Br.) A.Camus), kangaroo grass (*Themeda triandra*), cockatoo grass (*Alloteropsis semialata* (R.Br.) Hitchc.), cotton panic grass (*Digitaria brownii* (Roem. and Schult.) Hughes) (Cox 2012, 2013). There is increased demand for native species for landscape restoration associated with mining and road development, and for degraded grazing land (Cox 2012). In this area of Australia, a reliable seed industry has developed for the production of introduced grass species. This industry has developed capability to handle seed with a wide range of physical structures, including those that impede seed flow (Cox 2012).



**Table 2. Functional traits of some C<sub>3</sub> Australian native grasses that make them suitable for use in a changing climate (traits followed by 'a') and that need to be altered during the selection process leading to domestication (traits followed by 'b')**

Functional trait	Sources of the information are indicated by superscripts; where there are no superscripts, the information is based on the authors' experience					
	<i>Elymus rectisetus</i> (Nees) A.Löve and Connor	<i>Microloena stipoides</i> (Labill.) R.Br.	<i>Rytidosperma biparitum</i> (Link) A.M.Humphreys and H.P.Linder	<i>Rytidosperma caespitosum</i> (Gaudich.) Connor and Edgar	<i>Rytidosperma fulvum</i> (Vickery) A.M.Humphreys and H.P.Linder	<i>Rytidosperma richardsonii</i> (Cashmore) Connor and Edgar
Cultivars/selections						
	Murray	Griffin, Shannon, Wakefield, Tasman, Ovens	Bunderra	Trangie	Bidgee	Taranna, Hume
Life History						
Regenerative traits	Perennial (P) or annual (A)	P (a)	P (a)	P (a) short-lived	P (a)	P (a)
Flowering: determinate (D) or indeterminate (I)	D (a)	I (a)	I (a)	I (a)	I (a)	I (a)
Seed production (kg ha <sup>-1</sup> )	300 <sup>B</sup>	500 <sup>C</sup>	8–121 <sup>D</sup>	80 <sup>E</sup>	100 <sup>B</sup>	18–98 <sup>D</sup>
Seed shattering: present (P) absent (A)	P (b)	P (b)	P (b)	P (b)	P (b)	P (b)
Seed appendages: yes (Y) no (N)	Y (b)	Y (b)	Y (b)	Y (b)	Y (b)	Y (b)
Seed cleaning: need special equipment: yes (Y) no (N)	Y (a)	Y (a)	N (a)	N (a)	N (a)	N (a)
Primary dormancy: deep (P) non-deep (A)	A (a)	A (a) <sup>F</sup>	A (a) <sup>F</sup>	A (a) <sup>E</sup>	A (a) <sup>F</sup>	A (a) <sup>F</sup>
Germination, special requirements: yes (Y) no (N)	N (a)	N (a)	N (a)	N (a) <sup>E</sup>	N (a)	N (a)
Seed sowing, special equipment required: yes (Y) no (N)	N (a)	Y (b)	Y (b)	Y (b)	Y (b)	Y (b)
Seedling establishment, susceptible to weed competition: yes (Y) somewhat (S) no (N)	Y (b)	Y (b)	Y (b)	Y (b)	Y (b)	Y (b)
Forage quantity and quality	Annual forage production under good conditions (kg ha <sup>-1</sup> )	3400–7000 <sup>A</sup>	7400 <sup>G</sup>	5000–7800 <sup>H</sup>	?	5000–7800 <sup>H</sup>
Digestibility (%)	52 <sup>I</sup>	66–76 (a) <sup>J</sup>	45–74 <sup>H</sup>	45–47 <sup>E</sup>	?	45–74 <sup>H</sup>
Crude protein (%)	8–18 <sup>J</sup>	15.5–25 (a) <sup>I</sup>	10–17 <sup>H</sup>	10–17 <sup>E</sup>	?	10–17 <sup>H</sup>
Drought tolerance	high (H), moderate (M), low (L)	M	M	H	H	H
Invasiveness or weediness	high (H) moderate (M), low (L)	L	L	L	L	L

<sup>A</sup>Johnston *et al.* (1998). <sup>B</sup>Cole and Johnston (2006). <sup>C</sup>Whalley and Jones (1997). <sup>D</sup>Lodge (2002). <sup>E</sup>Waters (2009b). <sup>F</sup>Whalley (1987). <sup>G</sup>Robinson and Archer (1988). <sup>H</sup>Waters (2009a). <sup>I</sup>Foster *et al.* (2010). <sup>J</sup>Murphy (2001).

**Table 3. Functional traits of some C<sub>4</sub> Australian native grasses that make them suitable for use in a changing climate (traits followed by ‘a’) and that need to be altered during the selection process leading to domestication (traits followed by ‘b’)**

Functional trait	Attributes	Sources of the information are indicated by superscripts; where there are no superscripts, the information is based on the authors’ experience									
		<i>Alloteropsis semialata</i> (R.Br.) Hitchc. (Lindl.) Domin (Lindl.) F.Muell.	<i>Astrebla lappacea</i> (Lindl.) Domin (Lindl.) F.Muell.	<i>Astrebla pectinata</i> (Lindl.) F.Muell.	<i>Bothriochloa macra</i> (Steud.) S.T.Blake	<i>Dichanthium sericeum</i> (R.Br.) A.Camus	<i>Digitaria brownii</i> (Roem. and Schult.) Hughes	<i>Heteropogon contortus</i> (L.) P.Beauv. ex Roem. and Schult.	<i>Themeda triandra</i> Forsk.		
Cultivars/Selections		Yanda		Turanti		Lachlan, Bass		Scatta		Burrill, Mingo, Tangara	
Life History	Perennial (P) or annual (A)	P (a)	P (a)	P (a)	P (a)	P (a)	P (a)	P (a)	P (a)	P (a)	P (a)
Regenerative traits	Flowering: determinate (D) or indeterminate (I)	D?	I (a)	I (a)	I (a)	I (a)	I (a)	I (a)	I (a)	I (a)	I (a)
	Seed production (kg ha <sup>-1</sup> )	150–200 <sup>A</sup>	50–100 <sup>B</sup>	50–100 <sup>B</sup>	71 <sup>A</sup>	71 <sup>A</sup>	71 <sup>A</sup>	50–100 <sup>C</sup>	100 <sup>C</sup>	260–520 <sup>A</sup>	50–1800 <sup>B</sup>
	Seed shattering: present (P) absent (A)	?	A (a)	A (a)	P (b)	P (b)	P (b)	P (b)	A (a)	A (a)	P (b)
	Seed appendages: yes (Y) no (N)	Y (a)	Y (a)	Y (a)	Y (b)	Y (b)	Y (b)	Y (a)	Y (a)	Y (b)	Y (b)
	Seed cleaning: need special equipment: yes (Y) no (N)	N (a)	N (a)	N (a)	Y (a)	Y (a)	Y (a)	Y (a)	Y (a)	Y (a)	Y (a)
	Primary dormancy: deep (P) non-deep (A)	A (a) <sup>A</sup>	A (a) <sup>D</sup>	A (a) <sup>D</sup>	A (a) <sup>F</sup>	A (a) <sup>F</sup>	A (a) <sup>F</sup>	A (a) <sup>D</sup>	?	A (a) <sup>D</sup>	P (a) <sup>D</sup>
	Germination, special requirements: yes (Y) no (N)	?	N (a)	N (a)	N (a)	N (a)	N (a)	N (a)	N (a)	N (a)	Y (b)
	Seed sowing, special equipment required: yes (Y) no (N)	N (a)	N (a) <sup>E</sup>	N (a) <sup>E</sup>	N (a)	N (a)	N (a)	N (a)	Y (b)	Y (b)	Y (b)
	Seedling establishment, susceptible to weed competition: yes (Y) somewhat (S) no (N)	N (a)	N (a)	N (a)	Y (b)	Y (b)	Y (b)	S (b)	N (a)	Y (b)	Y (b)
Forage quantity and quality	Annual forage production under good conditions (kg ha <sup>-1</sup> )	?	2500 <sup>E</sup>	2500 <sup>E</sup>	3800–10 400 <sup>I</sup>	3800–10 400 <sup>I</sup>	3800–10 400 <sup>I</sup>	2000–5000	?	500–8700	8300 <sup>H</sup>
	Digestibility (%)	?	?	?	62 <sup>I</sup>	62 <sup>I</sup>	62 <sup>I</sup>	51% <sup>G</sup>	52% <sup>G</sup>	34% <sup>I</sup>	61% <sup>G</sup>
	Crude protein (%)	?	4.7–10.8% <sup>F</sup>	4.7–10.8% <sup>F</sup>	9 <sup>I</sup>	9 <sup>I</sup>	9 <sup>I</sup>	10% <sup>G</sup>	5.80% <sup>G</sup>	4–6% <sup>I</sup>	13.5% <sup>G</sup>
Drought tolerance	high (H) moderate (M) low (L)	L	M	M	H	H	H	M	H	H	H
Invasiveness or weediness	high (H) moderate (M) low (L)	L	L	L	M	M	M	L	L	L	L

<sup>A</sup>Cox (2012). <sup>B</sup>Cole and Johnston (2006). <sup>C</sup>Scattini (2008). <sup>D</sup>Whalley (1987). <sup>E</sup>Orr and Phelps (2008). <sup>F</sup>Waters et al. (2000). <sup>G</sup>Foster et al. (2010). <sup>H</sup>Archer and Robinson (1988). <sup>I</sup>Cook et al. (2005).

Many of the species that are and have been considered for pasture plantings in tropical areas have wide distributions. For example, *Heteropogon contortus* is native to tropical and subtropical areas of Africa, southern Asia, northern Australia and Oceania (Sharp and Simon 2002). Therefore, the potential exists to select and domesticate species from drier regions to cope with future predicted climates.

#### Functional traits that need changes

##### Seed production, seed shattering, seed harvesting and cleaning

The majority of species suitable for domestication for this region have indeterminate flowering and seed production dependent on rainfall. This means that seed can be produced over an extended period and allows seed producers to harvest the stands more than once a year. *Heteropogon contortus* produces a seed crop in May–July and then another in November–January (Cox 2012).

Many of the grass species that have been considered for domestication for these areas have less of a problem with seed shattering than those considered for temperate areas. Curly Mitchell grass (*Astrelba lappacea* (Lindl.) Domin) lends itself to direct heading because the seed does not shatter readily and a high proportion of the seed is retained on the head (Waters *et al.* 2000). Brush harvesting has been identified as the most effective method for harvesting *Alloteropsis semialata*, *Dichanthium sericeum* and *Heteropogon contortus* (Cox 2012).

##### Seed dormancy, seed germination and seed sowing

When considering native species for domestication for these environments, it is important to understand the function of the various seed appendages and whether these appendages play an important role in seed establishment. Many of these species have hygroscopic awns (e.g. *Dichanthium sericeum*, *Heteropogon contortus*, *Themeda triandra*) (Loch *et al.* 1996), which ensure that the falling seeds become embedded in the soil surface. A large range of equipment has been developed to process chaffy seeds, removing inert appendages and even the husk surrounding the caryopsis (Loch *et al.* 1996). Different methods suit different seed structures, and many of these methods and techniques have been developed overseas and have been readily adapted for use on indigenous species.

Engineering options have been used to overcome problems with sowing seed that is difficult to handle through conventional machinery. The crocodile seeder developed in Queensland has been successfully used to sow rough, unprepared sites (Waters *et al.* 2000). This machine is very robust, can be pulled by a tractor or four-wheel drive, and can be used to sow in areas of light timber.

##### Seedling establishment

Some undomesticated plants establish slowly, leaving them uncompetitive and difficult to use in most pasture production systems, so identification of species able to rapidly establish and compete with existing pasture species will be very important when developing new species for future climates. Smoke water has been used on a range of native species to enhance germination (Dixon *et al.* 1995; Read and Bellairs 1999; Clarke and French

2005). This technique has been used to overcome dormancy in *Heteropogon contortus*. However, in *Themeda triandra* the use of smoke water has been unsuccessful in overcoming dormancy, and dormancy remains an impediment to establishment (Cox 2012). This dormancy has been found to be highly persistent and appears to be related to the presence of the lemma and palea.

#### Mediterranean or low-rainfall semi-arid shrublands

A third important region is the semi-arid and arid zone Australia, in which the matrix species are C<sub>4</sub> shrubs (e.g. *Atriplex nummularia* Lindl. and *A. vesicaria* Heward ex. Benth) and the interstitial species are a mixture of forbs, legumes, and some C<sub>3</sub> and C<sub>4</sub> grasses, mostly annuals with some short-lived perennials (Graetz and Wilson 1984). The wheatbelt region of Western Australia and Mallee region of eastern Australia contain other chenopods such as *Maireana brevifolia* R.Br. Paul G. Wilson, *Atriplex semibaccata* R.Br., *A. bunburyana* F. Meull., and a range of *Rhagodia* species, including *Rhagodia preissii* Moq. The growth and reproduction of these communities is driven by rainfall events, and the season and quantity of each event governs the composition of the interstitial species (Graetz and Wilson 1984). Dryland salinity is another common feature of these agricultural landscapes. It is estimated that 1.1 Mha of agricultural land in Western Australia is severely salt-affected and a further 1.7–3.4 Mha is at risk (George *et al.* 2008). With a predominance of cereal cropping, perennial pastures tend to be grown on marginal soils. Salt tolerance, in addition to drought tolerance, is therefore very useful and shrubs from the family Chenopodiaceae are able to meet both criteria. We have selected seven of the species most likely to be good candidates for domestication (Table 4).

The most commonly planted chenopods include old man saltbush (*A. nummularia*) and river saltbush (*A. amnicola* Paul G. Wilson). Both are indigenous to the arid interior of Australia; therefore, it is relatively easy to achieve drought tolerance in higher rainfall agricultural zones. The drought-tolerance mechanisms of old man saltbush include deep roots (>4 m), osmotic control and slow growth when water is scarce (Barrett-Lennard 2003; Norman *et al.* 2010b).

There is a need for a legume component within these shrublands for N input, and introduced annual *Medicago* species have been present for many years, depending on the amount and pattern of rainfall events. Other introduced legumes such as *Trifolium subterraneum*, *T. cherleri* L., *T. hirtum* All., *T. tomentosum* L., *Biserrula pelecinus* L. and *Ornithopus compressus* L. may also be found in naturalised stands in the region. Another possibility is the use of *Acacia* species such as *A. ligulata* A. Cunn ex Benth. or *A. saligna* (Labill.) H.L. Wendl. (Revell *et al.* 2013). Given the long, dry summers that are typical of this region, the use of annual legumes for N fixation may be a more realistic target than domestication of native, perennial legumes. Although the more drought-tolerant chenopods do not fix N, they do provide high crude protein to livestock in summer and autumn, reducing the need for legumes to complement the low-protein grasses. In the context of the widespread salinity in this region, changing rainfall patterns may impact on the timing of salt-flushing rains (necessary for germination of salt-sensitive species), and

**Table 4. Functional traits of Australian native forage shrubs that make them suitable for use in a changing climate (traits followed by 'a') and that need to be altered during the selection process leading to domestication (traits followed by 'b')**

Functional trait	Attributes	<i>Acacia saligna</i> (Labiil.) H.L. Wendl.	<i>Atriplex amnicola</i> Paul G. Wilson	<i>Atriplex nummularia</i> Lindl.	<i>Atriplex semibaccata</i> R.Br.	<i>Atriplex vesticaria</i> Heward ex Benth.	<i>Enchyleana tomentosa</i> R.Br.	<i>Maireana brevifolia</i> R.Br. Paul G. Wilson	<i>Rhagodia pretsitii</i> Moq.
Life History	Perennial (P) or annual (A) Photosynthetic pathway	P C <sub>3</sub>	P C <sub>4</sub>	P C <sub>4</sub>	P (short-lived) ?	P C <sub>4</sub>	P ?	P C <sub>3</sub>	P ?
Regenerative traits	Bisexual (B), Monoecious (M) or Dioecious (D) Flowering: determinate (D) or indeterminate (I) Seed appendages: yes (Y) no (N)	B I Y, pods	D <sup>E</sup> I Y, bracts	D <sup>F</sup> (90%) I Y, bracts	M I Y, bracts	D I Y, bracts	B I N, fleshy fruits	B I Y, papery bracts	M I N, fleshy fruits
	Preparation for seeding	Dehull and scarify (mechanically or with acid) <sup>A</sup> Y, hard seed coat <sup>A</sup> >5 years Scarify mechanically or with acid <sup>A</sup>	Naked seed (threshed) or in bract Y <sup>F</sup> <2 years <sup>E</sup> Bracts inhibit germination. Spring sowing <sup>F</sup>	Naked seed (threshed) or in bract Y <sup>F</sup> <5 years <sup>E,F</sup> Bracts inhibit germination. Late winter, early spring sowing <sup>F</sup>	In bract Y <sup>F</sup> ?	Naked seed (threshed) or in bract Y <sup>K</sup> <5 years <sup>F</sup> ?	Pulp and dry ?	No processing ?	Pulp and dry ?
	Dormancy, yes (Y) no (N) Seed viability Germination, special requirements	S or T S S	T L (limited S)	S or T Limited S	S S, readily	S or T S, occasionally	T S, occasionally	S or T S, readily <sup>1</sup>	S or T N
Forage quantity and quality	Digestibility of organic matter (%) Crude protein (%) Ash (%) Known secondary compounds	35 ( <i>in vivo</i> ) <sup>B</sup> 13 <sup>B</sup> 8 <sup>B</sup> Tannins <sup>C</sup>	57 ( <i>in vivo</i> ) <sup>B</sup> 7-17 <sup>B,H</sup> 15-29 <sup>G</sup> Oxalates <sup>G</sup>	48-63 ( <i>in vivo</i> ) <sup>B</sup> 11-18 <sup>B,H</sup> 13-33 <sup>G</sup> Oxalates <sup>G</sup>	49 ( <i>in vivo</i> ) <sup>B</sup> 9.0-16.5 <sup>B,H</sup> 16-27 <sup>G</sup> Oxalates <sup>J</sup>	46 ( <i>in vitro</i> ) <sup>I</sup> 10-13 <sup>I</sup> 19-22 <sup>I</sup> Oxalates <sup>J</sup>	58 ( <i>in vitro</i> ) <sup>I</sup> 19 <sup>I</sup> 17-25 <sup>I</sup> Nitrates and oxalates	45 ( <i>in vivo</i> ) <sup>B</sup> 15-26 <sup>B,I</sup> 19-27 <sup>G</sup> Nitrates and oxalates <sup>E,G</sup>	67 ( <i>in vitro</i> ) <sup>H</sup> 12 <sup>B,I</sup> 16-22 <sup>I</sup> Saponins, oxalates <sup>I</sup>
Drought tolerance	Annual forage production under good conditions (kg DM/plant)	0.3-6.0	0.5-2.5 <sup>H,I</sup>	0.2-5.0 <sup>H,I</sup>	<0.4	0.2-2.0 <sup>I</sup>	0.2-2.0 <sup>I</sup>	0.2-1.0 <sup>I</sup>	0.2-2.5 <sup>I</sup>
Invasiveness or weediness	high (H) moderate (M) low (L)	H	H	H	M	H	H	H	H
Soil tolerances	high (H) moderate (M) low (L)	H <sup>D</sup>	L <sup>E,F</sup>	L <sup>E,F</sup>	M	L	L	M <sup>E,I</sup>	L
	Sand (S), Loam (L), Clay (C), waterlogged (WL), well drained (WD), saline (SA)	?	S, L, C, WD, WL, SA <sup>1</sup>	S, L, C, WD, SA <sup>1</sup>	S, L, C, WD, SA <sup>1</sup>	S, L, C, WD, SA <sup>1</sup>	S, L, C, WD, SA <sup>1</sup>	S, L, C, WD, SA <sup>1</sup>	S, L, C, WD <sup>1</sup>

Sources of the attribute information in the body of the Table are indicated by the superscripts in the Table cells. Where there are no superscripts, the information is based on the authors' experience.

<sup>A</sup>Ghassali *et al.* (2012). <sup>B</sup>Norman *et al.* (2010a). <sup>C</sup>Degen *et al.* (1995). <sup>D</sup>Emms *et al.* (2005). <sup>E</sup>Barrett-Lennard *et al.* (2003). <sup>F</sup>Nichols *et al.* (2014). <sup>G</sup>Norman *et al.* (2013).

<sup>H</sup>Norman *et al.* (2004). <sup>I</sup>Emms and Revell (2014). <sup>J</sup>Davis (1981). <sup>K</sup>Hunt (2001).



increased rainfall in summer could bring shallow watertables even closer to the soil surface, exacerbating the problem. Summer-active native perennials may be favoured by changing patterns and provide much-needed feed during summer and autumn.

#### Seed production

Seeds of chenopods are generally harvested in the summer by hand. This is labour-intensive; however, planting densities of <math><1000\text{ stems ha}^{-1}</math> mean that small quantities of seed may go a long way. Species vary in the rate of ripening and seed shedding. *Atriplex* seeds are enclosed within woody bracteoles and these fruits form regardless of successful fertilisation. It is very difficult to determine if there is actually a seed in the bracteoles. Nichols *et al.* (2014) purchased seed in bracteoles from a range of commercial suppliers and found that only 54–89% of bracts contained fruits. It is very difficult to assess bracteoles for seed-fill without soaking or X-ray scanning, and therefore sale of cleaned seed is encouraged although seed in bracteoles is thought to be better for direct seeding of some species (Nichols *et al.* 2014). The removal of bracteoles had a minor positive effect on laboratory germination for some species but this did not translate to improved field emergence (Stevens *et al.* 2006), probably because of the small size of the seed and need for very shallow sowing. Seed can be removed from bracteoles relatively simply by using commercial seed threshers or dehullers. Cleaning the seed is less simple and more time consuming because the seeds are very small and similar in size and weight to pieces of lignified bract. This seed varies widely in viability and germinability, which may be associated with environmental conditions during ripening, distance to mature male shrubs (for some *Atriplex* species) and genetic factors.

#### Seed dormancy and seed germination

Seed quality and germinability of chenopods can vary; for example, many of the seed batches of river saltbush tested by Vlahos *et al.* (1991) were shown to have germination rates <math><25\%</math> and only 10% of samples had germination rates >math>>50\%</math>. Gibberellic acid treatment of seed improves field establishment of river saltbush but had no impact on old man saltbush (Stevens *et al.* 2006). Seed quality declines with storage time, and *Atriplex* species lose most of their viability after 5 years of storage (Beadle 1952). Seeds of *Maireana* species are more sensitive and are generally harvested fresh each season. Recent work by H. Norman (unpublished data) shows that old man saltbush genotypes vary in bract size, seed size, ease of threshing, germinability and seedling growth rate.

#### Seedling establishment

There are difficulties with the establishment of chenopods. *Atriplex* species can be established either by seed sown with a specialised ‘niche seeder’ (Malcolm and Allen 1981) or as nursery-raised seedlings planted with a commercial tree-planter (Barrett-Lennard *et al.* 1991). These methods present trade-offs between cost and risk; niche seeding is relatively cheap but has a higher risk of failure and a longer lag time before grazing, whereas the planting of nursery-raised seedlings has lower risk and plants can be grazed much sooner but it is more costly (Barrett-Lennard

*et al.* 1991). Some species such as *Acacia* species, *M. brevifolia*, *Atriplex undulata*, *A. semibaccata* and *Rhagodia preissii* establish more readily by seed and may volunteer if plants are allowed to set seed.

#### Forage quantity and quality

The feeding value of native perennial species in the Mediterranean or low-rainfall, semi-arid shrublands is often poor. This is due to a combination of (i) low to moderate biomass production, (ii) low to moderate digestibility of the organic matter, (iii) excessive salt and/or sulfur accumulation, and (vi) excessive secondary compounds of plants such as tannins, oxalate, saponins and nitrates (Masters *et al.* 2007; Norman *et al.* 2010a; Revell *et al.* 2013). It is recommended that producers supplement livestock grazing native shrubs with crop stubbles, hay or grain (Norman *et al.* 2008), or feed mixtures of species with different nutritional profiles so that animals can balance their requirements (Revell *et al.* 2013). There has been little systematic effort to domesticate any of the native shrub species, and the majority of commercial plantations are derived from ‘wild’ seed lines.

Recent work has demonstrated an opportunity to improve the feeding value of chenopods by selecting genotypes with higher feeding value. This research has focused on old man saltbush in the first stages, as the species is already well adapted to low and variable rainfall, drought and salinity. It has value as a protein, sulfur, mineral and antioxidant supplement for ewes and weaners grazing cereal stubbles or senesced pastures (Norman *et al.* 2010b). On the negative side, it has a persistent rather than competitive ecological strategy, so growth can be slow, establishment from seed can be difficult and feeding value for livestock is variable. Whole-farm economic modelling suggests that low digestibility of the edible biomass (48–52% organic matter digestibility) is the critical trait influencing profitability and is therefore a target for plant improvement (O’Connell *et al.* 2006; Norman *et al.* 2010a). Unfortunately, plant domestication is a challenge because old man saltbush is both octoploid and dioecious.

The aim of plant domestication for old man saltbush is not to improve persistence in a changing climate (it is already well equipped to survive) but to overcome limitations to livestock production. In 2006, a collection of old man saltbush from across its native range was initiated and seed collected from 27 populations; 60 000 seedlings were grown in three nursery sites in New South Wales, South Australia and Western Australia (Hobbs and Bennell 2008). All plants were assessed for a range of agronomic traits and nutritive value was investigated at the provenance level. This involved a 2-year program of *in vivo* animal-house sheep-feeding experiments, development of *in vitro* analysis tools and calibration for near infrared spectroscopy (Norman and Masters 2010; Norman *et al.* 2010a). Each of the nursery sites was grazed with Merino sheep to assess relative palatability—perhaps one of the first times that animals have been used in the initial stages of plant-improvement programs to identify plants with higher nutritive value. The sheep at each site demonstrated clear preferences for plants originating from specific populations, and subsequent nutritive analyses indicated that these plants had higher organic matter digestibility and crude protein (Norman *et al.* 2011).

A series of agronomic screening and feeding experiments has resulted in the commercialisation of a new variety of old man saltbush in 2014. This variety, Anameka, will be sold to producers as nursery-raised vegetative cuttings and it has been shown to have higher organic matter digestibility and improved (relative) palatability to sheep (H. Norman, unpubl. data). The project team is now undertaking work to select elite seed lines to reduce establishment costs in nurseries and allow for direct seeding in paddocks.

### Plant introduction or domestication of native species?

Australia has a long history of introducing forage plants from similar bioclimates around the world to meet its agricultural needs (Cook and Dias 2006). Although there is no doubt that many valuable pasture plants have been introduced to Australia, many other introduced species have become serious weeds with significant ecological and economic impacts (Cook and Dias 2006; Stone *et al.* 2008). Native species are not exempt from becoming weeds. A native species translocated from one part of Australia to another can potentially become a weed. An example of this is *Acacia* (Bennett and Virtue 2005). Managing weed risk in native plants is a contentious issue, with the use of native plants seen as environmentally responsible and even patriotic (Bennett and Virtue 2005). As well as becoming weeds, native plants from different areas may genetically 'pollute' local populations and lead to decreased native diversity. The soil rhizobia that are utilised by legumes fit these criteria. It is important to ensure that introduction of new rhizobia for a novel legume does not reduce effectiveness of existing strains with existing species (Howieson *et al.* 1995). Many of the characteristics that are seen as ideal for production and persistence, e.g. seed production and natural regeneration, are often the characteristics that make such species weedy (Bennett and Virtue 2005).

It has been recognised as difficult to get landholders to re-sow pastures (Barr 1996; Trapnell *et al.* 2006), even with species and technologies that are well accepted and recognised. So the logical question is: why would a farmer adopt something that is less commonly used and often expensive? The impetus for adoption of new species and technologies may be reducing risk in the face of climate change, but only if there is sufficient information available with the release of new cultivars or species that farmers have the knowledge and confidence to fully capitalise on this risk. There is a need for paddock-scale quantification of costs and production as well as the development of extension packages for farmers and agribusiness to maximise potential benefits from using new cultivars and this should incorporate whole-farm management. The management strategies need to maximise productivity and persistence.

### Conclusions

Some level of certainty around climate change predictions is required before we change the direction of domestication programs. It is predicted that temperatures will increase, there will be higher potential evaporation and extreme weather events will be more common. Breeding or domestication programs typically have lead times of 10–15 years before material is released. Because many forage species are perennial, they

need to be assessed over several years and sites for adequate determination of traits such as persistence. Breeding for adaptation to new climatic environments is challenging.

If it cannot be demonstrated how these newer species or cultivars can increase profit or reduce risk and be established at a suitable cost, there will be very low uptake of these new technologies. For example, seed yield is low and cost of production is high for native grasses, because of the non-uniform times of seed production and rapid seed shedding (Oram and Lodge 2003; Cole and Johnston 2006). Therefore, in many instances, only high-return industries such as mining can afford to pay the full market price to sow native grasses. Establishment of old man saltbush by seed is inherently risky, whereas establishment from seedlings or cuttings is less risky and more expensive. Given that the productive life of stands can exceed 30 years, producers need to be confident that higher up-front costs will be recouped with a degree of certainty. There may well be a trade-off between nutritive value, biomass production in an ideal season and biomass production during a poor season. It is anticipated that livestock production systems will require some perennial plants that persist and provide moderate levels of feed of low–moderate quality with some annuals that are highly productive but risky.

The domestication of any species is an incremental and cyclic process of selection. There is uncertainty around exactly what future climates will be like. However, climate change is not new to Australia, and Australia's climate has gone through many cycles similar to those predicted for the next 50 years. Past climates have been hotter and drier, hotter and wetter, cooler and drier, and probably cooler and wetter. What is clear is that the capacity for adaptation to these changes has not been lost by massive plant extinctions in the recent geological past as have occurred in temperate parts of the northern hemisphere. Some Australian native plants have persisted or even remained common in areas where the advent of European agriculture has comprehensively changed the natural system, mainly because they have breeding systems that have enabled them to adapt to these dramatic changes. Others have not been able to adapt to these changes and so are rare or endangered. The former group is the one that shows the best potential for domestication to suit a changing climate. Pastures that have the best ability to cope with the changing climate are likely to consist of a suite of both C<sub>3</sub> and C<sub>4</sub> perennial species.

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