

# Prioritisation of native legume species for further evaluation as potential forage crops in water-limited agricultural systems in South Africa

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**Abstract** In the face of climate change, identification of forage species suitable for dryland farming under low rainfall conditions in South Africa is needed. Currently, there are only a limited number of forage species suitable for dryland farming under such conditions. The objective of this study was to identify and prioritise native legume species that could potentially be used in dryland farming systems in water-limited agro-ecosystems in South Africa. Using a combination of ecological niche modelling techniques, plant functional traits, and indigenous knowledge, 18 perennial herbaceous or

stem-woody legume species were prioritised for further evaluation as potential fodder species within water-limited agricultural areas. These species will be evaluated further for their forage quality and their ability to survive and produce enough biomass under water limitation and poor edaphic conditions.

**Keywords** Arid environments · Fabaceae · Leguminosae · Ecological niche models · Perennial forage species · South African native legumes

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## Introduction

The global demand for livestock products is expected to double by the year 2050, with the largest increases in demand occurring in the developing countries (Delgado et al. 2001; Herrero et al. 2009; Rao et al. 2015). With the rapidly growing human population and the projected future bioclimatic scenarios, significant trade-offs in the sustainable use of natural resources can be expected in order to meet these future demands for livestock products. These trade-offs could have significant impacts on the health, food security and livelihoods of various vulnerable populations (Luseno et al. 2003; McPeak 2006; Morton 2007; Thornton et al. 2007; Thornton et al. 2009; Herrero et al. 2009, 2015; Silvestri et al. 2012; Thornton and Herrero 2014). Countries in Sub-Saharan Africa are particularly vulnerable to climate change impacts. Within these countries, the projected climate change scenarios indicate a general trend of becoming hotter and drier

(Mukheibir 2008; Meissner et al. 2013a, b), and this, in turn, is expected to result in declines in agricultural production that will affect both food availability and access (IPCC 2007; Rufino et al. 2013). Furthermore, countries in Sub-Saharan Africa are affected by widespread poverty which limits their adaptive capacity to climate change. However, these countries have the largest potential to sustainably increase their livestock production systems through more efficient utilisation and management of natural resources (Silvestri et al. 2012, Rufino et al. 2013, Thornton and Herrero 2015).

To meet the future demand for livestock products, livestock production will have to increase in areas that are generally not regarded as highly productive, such as those characterised by water limitation, poor and restrictive edaphic, and marginal bioclimatic conditions. According to the United Nations Council on Combatting Desertification (UNCCD), approximately 80% of the South African land surface is classified as semi-arid to arid (Palmer and Ainslie 2006). However, approximately 82% of these areas are used for agricultural activities of which only 14% receive sufficient rainfall for arable crop production. The remainder of these areas are used for extensive livestock production, forestry and wildlife/nature conservation (Palmer and Ainslie 2006; Jordaan et al. 2013). Under these water-limited conditions, the most extensive agricultural activities are livestock (sheep, goat, cattle and ostrich) farming under rangeland conditions, where the livestock have to make use of the natural vegetation within these rangelands to meet their dietary requirements (Jordaan et al. 2013).

During dry periods, livestock production within these rangelands is often severely reduced due to a lack of good quality forage available to the livestock (Palmer and Ainslie 2006; Jordaan et al. 2013). In certain areas, where rainfall is less erratic, dryland fodder in the form of low input cereal crops are grown on cleared patches in between the natural vegetation. Crop residues that remain on these patches after harvest make an important contribution to livestock diets during these dry periods (Palmer and Ainslie 2006). However, the nutritional quality of these crop residues is generally poor, mainly due to their low palatability, nitrogen and available carbohydrate content (Brand et al. 2000; Brundyn et al. 2005). Often these cleared patches in between the natural vegetation are left uncultivated for extended periods of time due to the costs involved in their maintenance allowing unpalatable plants to occupy these spaces which further reduces the productivity of the rangelands.

However, these uncultivated lands in extensive livestock production systems could provide a means to sustainably increase livestock production within these marginal areas. In order to do so, good quality forage species that are well adapted to current and the projected future adverse bioclimatic and edaphic conditions need to first be identified. Currently, there is only a limited number of forage species, primarily old man saltbush (*Atriplex numularia* Lindl.) and spineless cactus (*Opuntia ficus-indica* (L.) Mill.), that are suitable for dryland farming within these water-limited areas (Palmer and Ainslie 2006; Dickinson et al. 2010; Truter et al. 2015). The use of these forage species is, however, limited in areas that fall within, or near, protected areas or, areas with high levels of endemism, due to their risk of becoming weedy or invasive. Also, these species are non-leguminous, and therefore, farmers do not have the added benefits of the symbiotic nitrogen fixation that legumes offer. The use of native leguminous species that are naturally adapted to these marginal areas would be a more sensible alternative than the non-leguminous, exotic germplasm, in order to diversify fodder flow programmes within water-limited agro-ecosystems.

In 2013, Trytsman (2013) produced a list of legume species from southern Africa for further characterisation and evaluation as potential forage crops. The selection of these species was based on six factors which included the distribution, height and life cycle of the plants, the presence of any anti-nutritional and toxic factors, adaptation to low soil phosphate conditions, and lastly, whether or not the plants were grazed/browsed and/or cultivated (Trytsman 2013). From this, Trytsman (2013) produced an extensive list of species with varying potential to be evaluated as possible forage species. Unfortunately, further efforts at evaluating these species have been minimal.

Several reasons exist for the lack of interest in evaluating and developing native legume species for forage production in South Africa itself. The most commonly reported reasons are the easily accessible exotic forage germplasm in South Africa (Palmer and Ainslie 2006; Trytsman 2013), large and well-known South African legume genera that are not generally recognised as livestock feed in South Africa itself, due to their perceived toxic qualities, the general lack of knowledge about their agronomic potential (Trytsman 2013), the time required to domesticate new forage species and the costs associated with producing marketable amounts of seeds (Loi et al. 2008; Nichols et al. 2007; Nichols et al. 2010; Muir et al. 2014; Mitchell et al. 2015). This, in

turn, resulted in forage breeding programmes in South Africa focussing primarily on producing exotic legume cultivars (e.g. *Medicago sativa* cv SA Standard and SA Select) that are adapted to specific agro-ecological conditions in South Africa (Palmer and Ainslie 2006; Trytsman 2013; Truter et al. 2015). As a result, the National Forage Genebank holds less than 5% of the native South African legume species that could be evaluated as possible forage crops, as opposed to nearly all native grass species (Trytsman 2013).

The identification of native legume species that are already well adapted to the water-limited and marginal edaphic and bioclimatic conditions would provide a more sustainable means to meet the demand for livestock products in South Africa. Also, with the general climate change trend in South Africa indicating hotter and drier conditions, new forage species that can withstand these conditions throughout South Africa is needed in order to prepare for future bioclimatic scenarios. The objective of this study was, therefore, to identify and prioritise native legume species that could potentially be used in dryland farming systems in South Africa.

## Materials and methods

### Species identification and selection

Distribution records of native legume species occurring in South Africa were obtained from the Global Biodiversity Facility (GBIF.org). The distribution records were cleaned by removing all incomplete and replicated data records. Thereafter, legume species occurring within the borders of the Northern Cape Province of South Africa were selected. The Northern Cape is characterised by large arid and semi-arid plains with a mean annual precipitation of 200 mm but ranges from 20 mm in the far West and up to 540 mm in the East. Temperatures range from as low as  $-10\text{ }^{\circ}\text{C}$  in winter to temperatures often exceeding  $40\text{ }^{\circ}\text{C}$  in the summer months (Jordaan et al. 2013). However, even under these extreme bioclimatic conditions, the Northern Cape houses a large diversity ( $\pm 402$  species) of indigenous legume species (GBIF.org). This makes the Northern Cape the ideal area to look for native legume species for water-limited agro-ecosystems.

The legume species occurring within the province were thereafter compared to a list of priority legume species from southern Africa produced by Trytsman

(2013). Legume species from the Northern Cape that occurred on the list by Trytsman (2013) were divided into different priority classes as described by Trytsman (2013). From this list, only species that occurred in the classes characterised by not having any known (from literature surveys) toxic or anti-nutritional qualities were selected (Trytsman 2013). Furthermore, all trees, climbers and creepers were removed from this list. This was due to climbers needing a host plant in order to be effective. Creepers were removed because the species identified need to be used as cut and carry crops, and trees were removed because of the time that it takes for a tree to grow and produce sufficient quantities of edible biomass under water-limited conditions. A further 13 legume species were identified as important livestock forages through informal interviews with botanists and pastoralists from the Northern Cape, as well as data gathered from following livestock to determine livestock diets in the communal rangelands of Leliefontein (Samuels et al. 2015). This meant that 13 species were added to the final list without being screened for containing anti-nutritional qualities. Thereafter, plant functional traits (Pérez-Harguindeguy et al. 2013) were used to further characterise the remaining legume species. Based on the availability of information, a total of 11 plant functional traits (Pérez-Harguindeguy et al. 2013) were used to describe the selected legume species with regards to their agronomic potential.

### Species distributions, climate and soil adaptation

The distribution records for the final selection of legumes occurring in the Northern Cape were plotted across their potential distribution range in South Africa using DivaGIS version 7.5 (Hijmans et al. 2001; Hijmans et al. 2005). The domain model (Carpenter et al. 1993) was used to estimate the climatic adaptation of the legume species using the 19 bioclimatic variables of the WorldClim climate database version 1.4 (Hijmans et al. 2005) at the resolution of 2.5 ARC minutes. The output Gower distance statistics generated by the domain model were categorised into four adaptation zones namely, 'Possible adaptation trend' (Gower scores of 50–70), 'adaptive trend' (Gower scores of 71–90), 'adapted range' (Gower scores of 91–95) and 'highly adapted range' (Gower scores of 96–100). The suitability of these adaptation zones was assessed by dividing the distribution records of *Lessertia frutescens* subsp. *frutescens* and *Indigofera alternans* into proportions of 25% (training

set) and 75% (testing set). The DOMAIN model was used to define these adaptation zones using the training sets while the testing set was used to calculate the proportion of the records for each of these species that fall within these adaptation zones. *Lessertia frutescens* subsp. *frutescens* and *Indigofera alternans* were used for this assessment as they contained the largest number of distribution records. Thereafter, maps of South Africa with ‘adapted’ and ‘highly adapted’ ranges were generated in DivaGIS. The grid files generated were imported into IDRISI (Terrset) after which the vector files were converted to raster images and adaptation ranges for each legume species quantified. The bioclimatic variables most limiting the adaptation of the native legume species were then identified using the DOMAIN Most Limiting Factor analysis in DivaGIS.

The prevalence of the different soil classes in South Africa (BGIS.org) was determined by calculating the area of each soil class using IDRISI. The distribution records of the selected legume species were thereafter plotted onto the different soil classes using ArcView version 3.3. The occurrence of each species within each soil class was calculated as a percentage of the total number of occurrence records for each legume species. The adaptation zones of each of the legume species were thereafter overlaid onto the different soil classes on which the legume species occur and clipped. The remaining areas were then calculated as the ‘new’ adaptation zones and were given as a percentage of the total surface area of South Africa.

## Results

### Species identification and selection

A total of 402 legume species in 67 genera were found within the borders of the Northern Cape (GBIF.org). Approximately 54% of the legume species found within the Northern Cape occur in only four genera namely, *Aspalathus* (18%), *Indigofera* (16%), *Lotononis* (12%) and *Lessertia* (8%) while 36 genera (11%) contain only one or two species. Of the 402 legume species, a total of 129 species were found on the list of priority species for further evaluation by Trytsman (2013), and after the removal of all species not occurring in Trytsmans’ categories of higher (A1), medium (B1) and lower (C1) forage potential, grazed/browsed, and/or cultivated as well as all trees,

creepers and climbers, a total of 24 legume species remained. A further 13 species identified as important livestock forages by the botanists and pastoralists from the Northern Cape were added to the list resulting in 37 initially selected legume species (Table 1).

Of the 11 plant functional traits initially selected, only seven had sufficient available information to use in the characterisation of the selected legume species. Table 2 provides information regarding the plant functional traits in the categories whole plant traits and reproductive traits for the initially selected legume species. The majority of the species on the list were found to have a perennial life cycle while only four species had an annual life cycle. A total of 27 species were found to have a herbaceous growth form and all species had terminally placed seed pods. Only perennial, herbaceous, stem woody, spineless and species not already being developed as forage crops elsewhere (i.e. *Lebeckia ambigua* (Howieson et al. 2013, De Meyer et al. 2014)) were selected for further screening. Therefore, only 18 legume species remained and were considered for the remainder of the work that focused on the climate and soil adaptability of the species.

### Distribution and climate adaptation

Potential distribution ranges, determined from the output Gower statistics for each of the legume species, are shown in Fig. 1. Nine of the legume species (*Crotalaria pearsonii*, *Crotalaria excisa* subsp. *namaquensis*, *Calobota sericea*, *Indigofera meyeriana*, *Lesseria diffusa*, *Lessertia excisa*, *Lessertia incana*, *Lessertia inflata* and *Psolarea glaucescens*) were only found within the boundaries of two or three provinces i.e. Northern Cape, Western Cape and Eastern Cape or North West Province. The remaining nine legume species (*Crotalaria laburnifolia* subsp. *laburnifolia*, *Cullen tomentosum*, *Indigofera alternans* var. *alternans*, *Indigofera heterotricha*, *Indigofera nigromontana*, *Lessertia depressa*, *Lessertia pauciflora* var. *pauciflora*, *Lessertia frutescens* subsp. *frutescens* and *Senna italica*) had distribution records that span across the boundaries of five to seven of the South African provinces. A total of seven species (*Cullen tomentosum*, *Indigofera alternans*, *Indigofera heterotricha*, *Lessertia depressa*, *Lessertia pauciflora* var. *pauciflora*, *Senna italica* and *Lessertia frutescens* subsp. *frutescens*) were found to have a combined ‘adapted’ and ‘highly adapted’ range covering over 40% of the South Africa’s land surface (Fig. 1).

**Table 1** Selected native legume species from the Northern Cape Province of South Africa using Trytsman’s (2013) prioritised categories and those species identified as important livestock

forages in the Northern Cape. High priority (A1), moderate priority (B1), grazed/browsed (\*), cultivated (+), identified as important by farmers and botanists (△△)

Name	Use
1 <i>Crotalaria effusa</i> E.Mey.	* △△
2 <i>Crotalaria excisa</i> (Thunb.) Baker f. subsp. <i>namaquensis</i> Polhill	* △△
3 <i>Crotalaria laburnifolia</i> L. subsp. <i>laburnifolia</i>	+ △△
4 <i>Crotalaria pearsonii</i> Baker f.	B1
5 <i>Cullen tomentosum</i> (Thunb.) J.W.Grimes	+ B1
6 <i>Indigostrum argyroides</i> (E.Mey.) Schrire	*
7 <i>Indigofera alternans</i> DC. var. <i>alternans</i>	* A1
8 <i>Indigofera heterotricha</i> DC.	B1
9 <i>Indigofera meyeriana</i> Eckl. & Zeyh	*
10 <i>Indigofera nigromontana</i> Eckl. & Zeyh.	+ △△
11 <i>Indigofera pungens</i> E.Mey	*
12 <i>Lebeckia ambigua</i> E.Mey.	*
13 <i>Calobota sericea</i> (Thunb.) Boatwr. & B-E.van Wyk ( <i>Lebeckia sericea</i> Thunb.)	* △△
14 <i>Calobota spinescens</i> (Harv.) Boatwr. & B-E.vanWyk ( <i>Lebeckia spinescens</i> Harv.)	*
15 <i>Lessertia brachypus</i> Harv	* △△
16 <i>Lessertia depressa</i> Harv	* A1
17 <i>Lessertia diffusa</i> R.Br	*
18 <i>Lessertia excisa</i> DC.	*
19 <i>Lessertia frutescens</i> (L.) Goldblatt & J.C. Manning subsp. <i>frutescens</i>	* B1
20 <i>Lessertia frutescens</i> (L.) Goldblatt & J.C. Manning subsp. <i>microphylla</i> (Burch ex DC.) J.C.Manning & Boatwr.	+ A1
21 <i>Lessertia incana</i> Schinz	*
22 <i>Lessertia inflata</i> Harv	*
23 <i>Lessertia pauciflora</i> Harv. var. <i>pauciflora</i>	* A1
24 <i>Lessertia spinescens</i> E.Mey	*
25 <i>Lotononis falcata</i> (E.Mey.) Benth	* △△
26 <i>Lotononis leptoloba</i> Bolus	* △△
27 <i>Melolobium adenodes</i> Eckl. & Zeyh.	* △△
28 <i>Melolobium humile</i> Eckl. & Zeyh.	* △△
29 <i>Melolobium microphyllum</i> (L.f.) Eckl. & Zeyh	B1
30 <i>Melolobium obcordatum</i> Harv.	A1
31 <i>Psoralea glaucescens</i> Eckl. & Zeyh.	* △△
32 <i>Rhynchosia adenodes</i> Eckl. & Zeyh.	A1
33 <i>Rhynchosia emarginata</i> Germish	*
34 <i>Rhynchosia schlechteri</i> Baker f	* △△
35 <i>Senna italica</i> Mill. subsp. <i>arachoides</i> (Burch.) Lock	+ B1
36 <i>Wiborgia fusca</i> Thunb. subsp. <i>fusca</i>	* △△
37 <i>Wiborgia monoptera</i> E.Mey	*

The results of the analysis of the most limiting bioclimatic factors influencing the distributions of the legume species in South Africa are shown in Table 3. Based on the two major bioclimatic themes (temperature and

precipitation) of the WorldClim climate database, the 18 native legume species can be divided into three broad categories. The first category consists of a total of seven legume species (*Crotalaria laburnifolia*, *Crotalaria*

**Table 2** Plant functional traits used to characterise native legume species for their forage potential

Name	Life cycle	Height [up to (m)]	Growth form	Growth habit	Spines	Flower-fruit time	Fruit placement	Fruit size (mm long)	Fruit attributes	Seed size (mm long)	Seeds per pod
<i>Calobota sericea</i> <sup>1,2</sup>	P	1.8	SW	Erect	No	May-Oct	Terminal	-	Dehiscent	-	-
<i>Calobota spinescens</i> <sup>1,2</sup>	P	1	W	Erect	Yes	Sept-May	Terminal	-	Dehiscent	-	-
<i>Crotalaria effusa</i> <sup>4</sup>	A	0.7	H	-	-	-	Terminal	-	-	-	-
<i>Crotalaria excisa</i> <sup>1,2</sup>	P	1.2	H	Sprawling	No	Aug-Oct	Terminal	20-25	-	-	-
<i>Crotalaria laburnifolia</i> subsp. <i>laburnifolia</i> <sup>4</sup>	P	2	H	-	-	-	Terminal	-	-	-	-
<i>Crotalaria pearsonii</i> <sup>2</sup>	P	0.5	H	Erect	No	Aug-Nov	Terminal	18-35	Dehiscent	2-4	-
<i>Cullen tomentosum</i> <sup>4</sup>	P	1.2	H	Prostrate	No	July-Jan	Terminal	-	-	-	-
<i>Indigostrum argyroides</i> <sup>2</sup>	A	0.5	H	Prostrate	No	Sept-May	Terminal	-	-	-	-
<i>Indigofera alternans</i> subsp. <i>alternans</i> <sup>4</sup>	P	2	H	Prostrate	No	Sept-Dec	Terminal	< 10	-	-	6-8
<i>Indigofera heterotricha</i> <sup>4</sup>	P	1.5	H	Erect	No	-	Terminal	-	-	-	8
<i>Indigofera meyeriana</i> <sup>1,2</sup>	P	1	H	Prostrate	No	Jun-Nov	Terminal	-	-	-	-
<i>Indigofera nigromontana</i> <sup>1</sup>	P	1.5	H	-	No	-	Terminal	-	-	-	-
<i>Indigofera pungens</i> <sup>2</sup>	P	1.2	SW	Erect	Yes	May-Oct	Terminal	-	-	-	-
<i>Lebeckia ambigua</i> <sup>1,2</sup>	P	0.8	H	Erect	-	Aug-Dec	Terminal	-	Dehiscent	-	-
<i>Lessertia brachypus</i> <sup>2,3</sup>	P	1	H	Erect	No	July-Aug	Terminal	-	-	-	-
<i>Lessertia depressa</i> <sup>1,3</sup>	P	0.6	H	Prostrate	No	Jun-Dec	Terminal	10-15	-	-	-
<i>Lessertia diffusa</i> <sup>1-3</sup>	P	0.5	H	Sprawling	No	Aug-Sept	Terminal	10-15	-	-	6-8
<i>Lessertia excisa</i> <sup>1,3</sup>	P	0.4	H	Procumbent	No	Aug-Oct	Terminal	-	-	-	-
<i>Lessertia incana</i> <sup>1-3</sup>	P	0.6	H	-	No	Sept-Nov.	Terminal	-	-	-	-
<i>Lessertia inflata</i> <sup>2,3</sup>	P	0.2	H	Decumbent	No	Aug-Dec	Terminal	10-15	-	-	-
<i>Lessertia pauciflora</i> var. <i>pauciflora</i> <sup>3</sup>	P	1.2	H	Prostrate	No	-	Terminal	30-43	-	-	10-12
<i>Lessertia spinescens</i> <sup>1-3</sup>	P	0.8	H	Erect	Yes	Aug-Sept	Terminal	-	-	-	1-2
<i>Lessertia frutescens</i> subsp. <i>frutescens</i> <sup>1-3</sup>	P	1.3	H	Erect	No	-	Terminal	-	-	-	-
<i>Lessertia frutescens</i> subsp. <i>microphylla</i> <sup>1-3</sup>	P	1.3	H	Erect	No	-	Terminal	-	-	-	-
<i>Lotononis falcata</i> <sup>1,2</sup>	A	0.3	H	Prostrate	-	May-Sept.	Terminal	-	-	-	-
<i>Lotononis leptoloba</i> <sup>1,2</sup>	A	0.8	H	Sprawling	-	Sept-Oct.	Terminal	-	-	-	-
<i>Melolobium adenodes</i> <sup>1,2,4</sup>	P	0.3	H	-	Yes	Sept-Oct.	Terminal	-	-	-	-
<i>Melolobium humile</i> <sup>1,2</sup>	P	0.5	H	-	Yes	Sept-Oct.	Terminal	-	-	-	-

Table 2 (continued)

Name	Life cycle	Height [up to (m)]	Growth form	Growth habit	Spines	Flower-fruit time	Fruit placement	Fruit size (mm long)	Fruit attributes	Seed size (mm long)	Seeds per pod
<i>Melolobium microphyllum</i> <sup>4</sup>	P	1	W	Branched	Yes	-	Terminal	12-18	Dehiscent	2-3	2-4
<i>Melolobium obcordatum</i> <sup>4</sup>	P	0.5	W	Decumbent	Yes	-	Terminal	12-16	Dehiscent	2-2.3	2-4
<i>Psoralea. Glaucescens</i> <sup>2</sup>	P	3	H	Branched	-	Nov.-Apr.	-	-	-	-	-
<i>Rhynchosia adenodes</i>	P	0.6	W	Prostrate	No	?	Terminal	-	-	-	-
<i>Rhynchosia emarginata</i> <sup>2</sup>	P	0.8	W	Erect	No	Aug.-Sept.	Terminal	-	-	-	-
<i>Rhynchosia schlechteri</i> <sup>2</sup>	P	0.4	W	?	?	Jul-Sept	Terminal	-	-	-	-
<i>Sena italica</i> subsp. <i>arachoides</i> <sup>4</sup>	P	1	H	Erect	No	?	Terminal	-	-	-	5-7
<i>Wiborgia fusca</i> <sup>1,2</sup>	P	1.6	W	Erect	Yes	Aug.-Oct.	Terminal	-	-	-	-
<i>Wiborgia monoptera</i> <sup>2</sup>	P	1	W	Erect	Yes	Jul-Sept	Terminal	-	Indehiscent	-	-

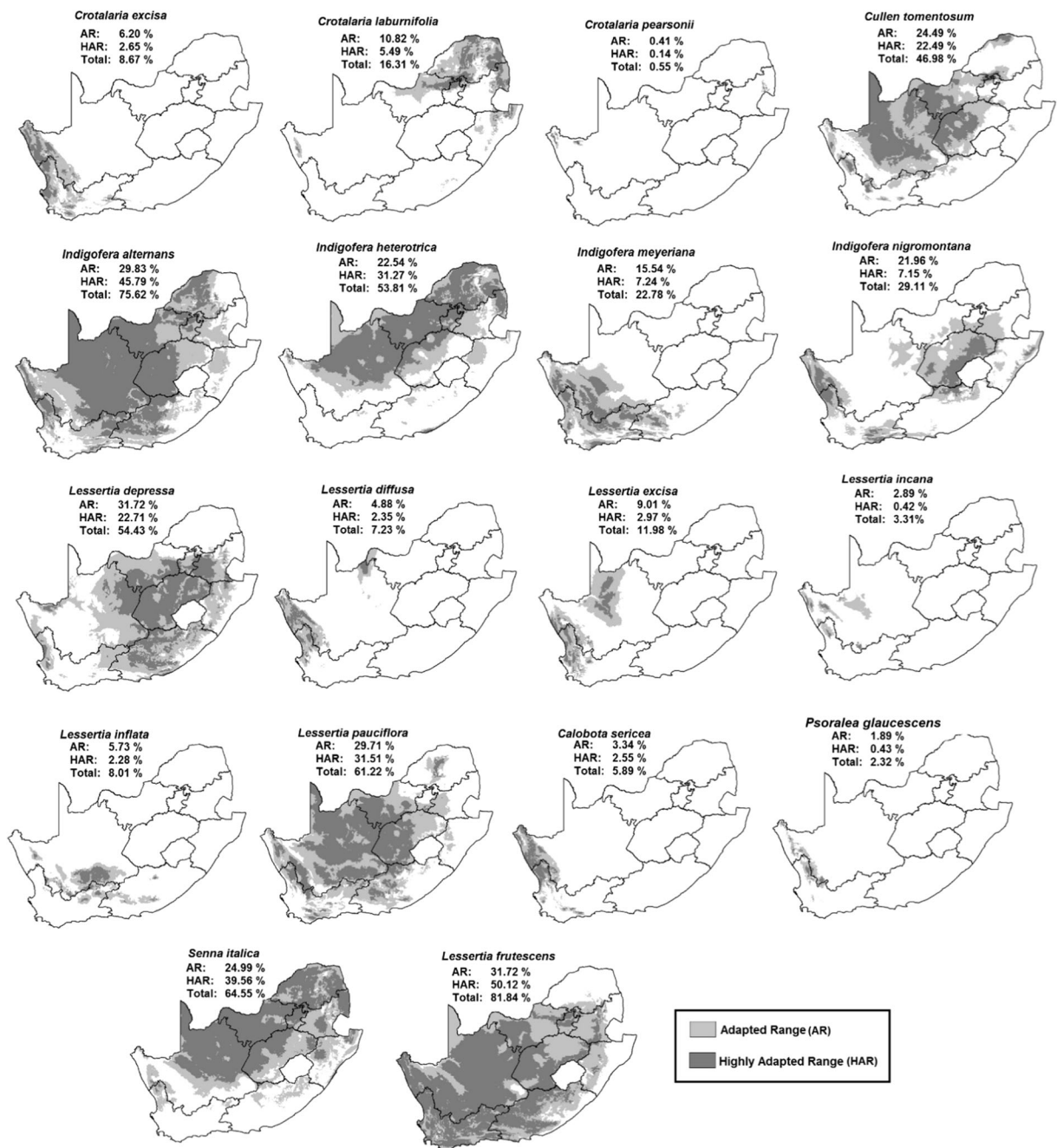
A annual, P perennial, SW stem woody, W woody, H herbaceous

1= Schutte 2012, 2= Campbell-Young 2013, 3= Nkonki 2013, 4= Nkonki et al. 2003

*pearsonii*, *Indigofera alternans* var. *alternans*, *Indigofera nigromontana*, *Lessertia pauciflora* var. *pauciflora*, *Lessertia frutescens* subsp. *frutescens* and *Psolarea glaucescens*) that have distributions limited primarily by temperature variables. The second category consisted of six legume species (*Calobota sericea*, *Crotalaria excisa*, *Indigofera meyeriana*, *Lessertia diffusa*, *Lessertia excisa*, and *Lessertia incana*) that have distributions limited primarily by precipitation variables. The third category consisted of six legume species (*Cullen tomentosum*, *Indigofera heterotricha*, *Lessertia depressa*, *Lessertia inflata* and *Senna italica*) that have distributions limited by a combination of temperature and precipitation variables.

Soil adaptations and new adaptation zones

Table 4 shows the percentage that the 19 general soil classes contribute to the total land surface of South Africa as well as the occurrence (given as a percentage of the total distribution records for each species) of each of the native legume species within each of the general soil classes. Three soil classes namely Arenosols 2 (AR2), Leptosols 2 (LP2) and Regosols (R) were found to be the most common soil classes on which the largest percentage of occurrence records for most of the native legume species were recorded (Table 4). Arenosols 2 are red and yellow, well-drained sandy soils with high base status. Leptosols 2 are soils with minimal development. They are usually shallow, on hard or weathering rock, with or without intermittent diverse soils and lime is generally present in part or most of the landscape. Regosols are characterised as rocky areas with limited soil (FAO 2005). After overlaying the ‘adapted’ and ‘highly adapted’ ranges of the legume species on the different soil classes, and clipping only those soil classes with occurrence records, a significant reduction in the overall ‘adapted’ and ‘highly adapted’ ranges were observed. Table 5 provides the new ‘adapted’ and ‘highly adapted’ ranges of the native legume species as a percentage of the total land surface of South Africa. From this table, those seven species (*Cullen tomentosum*, *Indigofera alternans* subsp. *alternans*, *Indigofera heterotricha*, *Lessertia depressa*, *Lessertia pauciflora* var. *pauciflora*, *Senna italica* and *Lessertia frutescens* subsp. *frutescens*) that had a combined ‘adapted’ and ‘highly adapted’ range covering over 40% of the total South African land surface remained the species with the largest ‘adapted’ and ‘highly adapted’ ranges (Table 5).



**Fig. 1** Adapted and highly adapted ranges of 18 native legume species from South Africa

## Discussion

### Prioritisation of native legume species

The initial prioritisation of the native legume species was done primarily on the basis of their life cycle, growth form and degree of spinescens. This led to the selection of

only perennial, herbaceous or stem-woody and spineless species from the 37 species identified. The selection of species with herbaceous or stem-woody growth habits was based on the idea that these species would have a higher relative growth rate compared to woody species (Hunt and Cornelissen 1997; Houghton et al. 2013). Therefore, due to the short-wet seasons usually



**Table 3** The percentage of South Africa's total land surface (rounded to the nearest integer) where variables of the WorldClim climate database is most limiting the adaptation of each of the native legume species

	BIO 1	BIO 2	BIO 3	BIO 4	BIO 5	BIO 6	BIO 7	BIO 8	BIO 9	BIO 10	BIO 11	BIO 12	BIO 13	BIO 14	BIO 15	BIO 16	BIO 17	BIO 18	BIO 19
exc.	2	1	1	0	0	0	0	21	3	1	2	0	0	1	2	0	1	65	0
lab.	1	5	6	43	1	5	0	0	12	1	0	1	0	5	7	1	5	1	6
pea.	0	0	1	0	0	5	0	0	51	0	0	0	0	0	19	0	5	0	19
tom.	1	5	17	6	5	6	0	2	3	4	1	1	6	18	2	2	6	12	3
alt.	5	11	12	7	2	11	2	3	4	6	2	1	2	11	7	0	3	10	1
het.	1	4	23	2	1	10	1	8	9	1	0	5	3	12	8	1	5	2	4
mey.	0	1	7	2	0	1	0	2	2	1	5	0	46	0	6	18	0	9	0
nig.	2	17	19	7	1	1	1	6	1	2	2	2	20	8	3	1	1	2	4
dep.	7	5	11	3	1	2	1	3	4	2	7	2	15	2	11	10	4	5	5
dif.	1	1	4	0	0	1	0	6	5	1	5	10	12	3	1	2	5	42	1
exci.	2	5	3	0	1	1	0	8	4	0	3	0	4	1	5	0	0	63	0
inc.	1	1	3	0	0	1	0	2	2	0	1	1	27	1	3	24	5	25	3
inf.	3	29	3	2	1	1	0	1	1	8	0	1	23	1	4	10	6	5	1
pau.	6	5	12	6	1	10	6	2	4	2	7	2	4	2	3	5	3	16	4
ser.	0	0	2	1	0	1	0	7	23	1	0	1	7	0	0	1	0	55	1
gla.	6	5	12	6	1	10	7	2	4	2	7	2	4	2	3	5	3	15	4
ita.	2	2	20	4	5	3	1	2	2	6	3	3	1	9	21	3	4	2	7
fru.	5	6	17	8	1	5	1	2	2	1	12	3	8	2	21	2	1	2	1

Species names are abbreviated as: exc.: *C. excisa*, lab: *C. laburnifolia*, pea: *C. pearsonii*, alt: *I. alternans*, het: *I. heterotricha*, mey: *I. meyeriana*, nig: *I. nigromontana*, dep: *L. depressa*, dif: *L. diffusa*, exci: *L. excisa*, inc: *L. incana*, inf: *L. inflata*, pau: *L. pauciflora*, gla: *P. glaucescens*, ita: *S. italica*, tom: *C. tomentosum*, ser: *C. sericea*, fru: *L. frutescens*. BIO1 = Annual Mean Temperature; BIO2 = Mean Diurnal Range (Mean of monthly (max temp–min temp)); BIO3 = isothermality (BIO2/BIO7) (\* 100); BIO4 = temperature seasonality (standard deviation \*100); BIO5 = max temperature of warmest month; BIO6 = min temperature of coldest month; BIO7 = temperature annual range (BIO5–BIO6); BIO8 = mean temperature of wettest quarter; BIO9 = max temperature of driest quarter; BIO10 = mean temperature of warmest quarter; BIO11 = mean temperature of coldest quarter; BIO12 = annual precipitation; BIO13 = precipitation of wettest month; BIO14 = precipitation of driest month; BIO15 = precipitation seasonality (coefficient of variation); BIO16 = precipitation of wettest quarter; BIO17 = precipitation of driest quarter; BIO18 = precipitation of warmest quarter; BIO19 = precipitation of coldest quarter

**Table 4** Percentage of each soil class in South Africa, the percentage of the total species distributions on individual soil classes and their associated soil pH ranges

Soil Class	Soil as a % of SA	exc.	lab.	pea.	tom.	alt.	het.	mey.	nig.	dep.	dif.	exci.	inc.	inf.	pau.	gla.	ita.	ser.	fru.
AC	4.5	5	2	-	-	1	1	-	-	1	-	3	-	-	-	-	-	-	2
AR1	4.1	-	-	-	5	8	2	-	3	-	-	-	-	-	4	-	5	-	-
AR2	9.1	11	5	25	17	9	14	1	7	11	30	11	25	-	8	8	19	21	6
AR3	1.3	11	-	-	-	-	-	-	-	-	5	7	-	-	-	-	-	-	1
CM	8.1	8	12	-	25	9	20	7	4	9	3	-	-	-	9	-	22	5	3
FL	1.2	-	2	-	-	2	2	-	-	-	-	-	-	-	-	-	2	-	1
FR	0.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LP1	7.8	-	14	-	-	-	10	-	4	7	-	-	-	-	-	-	6	-	2
LP2	28.4	37	20	25	25	33	16	50	7	19	27	18	75	50	47	43	15	45	40
NT	0.6	-	5	-	-	1	3	-	7	-	-	-	-	-	-	-	2	-	-
PH	1.4	-	5	-	3	1	1	-	-	6	-	-	-	-	1	-	-	-	-
PL1	4.5	3	0	-	3	17	-	7	-	13	-	7	-	25	9	-	1	-	6
PL2	8	3	5	-	8	8	1	5	30	11	5	11	-	5	7	8	5	-	6
PT1	4.4	-	-	-	-	1	6	-	-	4	-	-	-	-	1	-	3	-	1
PT2	4.5	-	12	-	2	2	10	-	15	4	3	4	-	-	1	8	11	-	-
PZ	0.2	-	-	-	-	-	-	-	4	-	-	-	-	-	-	-	-	-	1
R	8	22	16	25	7	5	11	30	19	11	27	39	-	20	9	33	9	29	28
SC	1.6	-	-	25	5	2	-	-	-	-	-	-	-	-	3	-	-	-	3
VR	2.1	-	2	0	-	1	3	-	-	4	-	-	-	-	1	-	-	-	-
W	0.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Soil pH		5.5-7.4	5.5-7.4	5.5-7.5	6.5-8.4	6.5-7.4	5.5-7.4	6.5-8.4	6.4-7.4	6.5-8.4	6.5-8.4	5.5-8.4	6.5-8.4	6.5-8.4	6.5-8.4	6.5-8.4	5.5-7.4	6.5-8.4	6.4-7.5

A dash (-) represents the absence of distribution records on a soil. Species names are abbreviated as: exc.: *C. excisa*, lab: *C. laburnifolia*, pea: *C. pearsonii*, alt: *I. alternans*, het: *I. heterotricha*, mey: *I. meyeriana*, nig: *I. nigromontana*, dep: *L. depressa*, dif: *L. diffusa*, exci: *L. excisa*, inc: *L. incana*, inf: *L. inflata*, pau: *L. pauciflora*, gla: *P. glaucescens*, ita: *S. italica*, tom: *C. tomentosum*, arg: *I. argyroides*, ser: *C. sericea*, fru: *L. frutescens*, Acrisols (AC), Arenosols1 (AR1), Arenosols2 (AR2), Arenosols3 (AR3), Cambisols (CM), Fluviosols (FL), Ferralsols (FR), Leptosols1 (LP1), Leptosols2 (LP2), Nitisols (NT), Phaezems (PH), Luvisols1 (PL1), Luvisols2 (PL2), Plinthosols1 (PT1), Plinthosols2 (PT2), Podzols (PZ), Regosols (R), Solonchaks (SC), Vertisols (VR), Water (W), Trytsman (2013)

**Table 5** Percentage of the ‘new’ ‘adapted’ and ‘highly adapted’ ranges on different soil classes in South Africa

	AC	AR1	AR2	AR3	CM	FL	LP1	LP2	NT	PH	PL1	PL2	PT1	PT2	PZ	R	SC	VR	Total (%)
exc.	A	0.06	-	0.18	0.02	-	-	1.08	-	-	-	-	-	-	-	1.15	-	-	4.97
	HA	0.03	-	0.24	0.06	-	-	0.42	-	-	-	-	-	-	-	0.44	-	-	
lab.	A	0.90	-	0.96	1.62	0.15	1.17	1.96	0.21	0.21	-	0.42	-	0.94	-	0.85	-	0.48	15.08
	HA	0.17	-	0.27	1.11	0.12	0.51	1.48	0.18	0.12	-	0.20	-	0.54	-	0.27	-	0.25	
pea.	A	-	-	0.07	-	-	-	0.11	-	-	-	-	-	-	-	0.07	0.02	-	0.36
	HA	-	-	0.02	-	-	-	0.04	-	-	-	-	-	-	-	0.02	0.02	-	
tom.	A	-	4.46	3.22	2.24	-	-	6.98	-	0.03	2.39	2.14	-	1.74	-	1.53	0.36	-	51.01
	HA	-	6.75	4.04	3.55	-	-	6.45	-	0.19	0.42	1.71	-	1.11	-	0.70	1.02	-	
alt.	A	1.25	0.18	1.50	0.00	0.39	-	8.63	0.14	0.23	-	-	3.13	2.10	-	3.35	0.36	1.44	62.30
	HA	0.25	3.87	7.23	0.00	0.56	-	13.78	0.08	0.21	-	-	0.43	2.10	-	2.32	1.06	0.49	
het.	A	2.77	2.01	2.14	-	2.10	0.22	4.20	0.21	0.51	-	2.87	1.76	0.94	-	1.07	-	1.02	55.39
	HA	2.56	1.97	5.29	-	5.19	0.29	1.31	0.20	0.08	-	1.14	1.59	3.01	-	1.56	-	0.77	
mey.	A	-	-	1.41	0.08	-	-	8.45	-	-	0.71	3.23	-	-	-	2.53	-	-	24.79
	HA	-	-	0.38	0.08	-	-	4.63	-	-	0.26	1.90	-	-	-	1.13	-	-	
nig.	A	-	0.04	1.69	1.82	-	1.52	4.33	0.06	-	-	2.91	-	1.24	0.04	1.96	-	-	21.45
	HA	-	0.03	0.41	0.33	-	0.09	1.52	0.04	-	-	2.37	-	0.45	0.01	0.60	-	-	
dep.	A	2.06	-	4.51	2.01	-	2.29	8.76	-	0.31	1.73	2.44	1.85	1.27	-	2.21	-	0.33	51.98
	HA	0.52	-	1.68	2.58	-	0.93	4.30	-	0.45	2.14	3.93	1.91	1.86	-	0.88	-	1.05	
dif.	A	-	-	1.64	0.07	-	-	1.72	-	-	-	0.18	-	0.00	-	0.58	-	-	6.62
	HA	-	-	0.91	0.02	-	-	0.80	-	-	-	0.03	-	0.01	-	0.37	-	-	
exci.	A	0.06	1.95	1.06	0.17	0.28	0.18	3.42	-	-	0.07	0.31	0.01	0.004	0.003	0.84	0.55	-	11.89
	HA	0.03	0.48	0.52	0.12	0.07	0.03	1.12	-	-	0.06	0.11	-	0.01	-	0.26	0.09	-	
inc.	A	-	0.04	0.52	0.03	0.02	-	1.80	-	-	0.001	0.004	-	-	-	0.12	0.33	-	3.30
	HA	-	0.02	0.14	-	-	-	0.20	-	-	0.01	0.01	-	-	-	0.03	0.01	-	
inf.	A	0.003	0.24	0.003	0.20	0.20	0.04	3.56	-	-	0.72	0.15	-	0.01	-	0.49	0.12	-	7.99
	HA	-	0.12	0.01	0.01	0.03	0.02	1.28	-	-	0.49	0.08	-	0.003	-	0.22	0.01	-	
pau.	A	-	0.57	2.67	1.54	-	-	10.19	-	0.07	1.50	2.64	1.90	1.87	-	2.74	0.44	1.34	58.46
	HA	-	3.34	4.67	3.71	-	-	9.80	-	0.18	2.73	2.51	0.20	1.50	-	1.20	1.05	0.09	
ser.	A	-	-	0.58	0.01	-	-	1.45	-	-	-	-	-	-	-	0.59	-	-	5.00
	HA	-	-	0.65	0.05	-	-	1.17	-	-	-	-	-	-	-	0.50	-	-	
gla.	A	-	-	0.20	-	-	-	1.03	-	-	-	0.02	-	0.55	-	0.43	-	-	3.27
	HA	-	-	0.02	-	-	-	0.21	-	-	-	0.02	-	0.69	-	0.10	-	-	
ita.	A	-	0.13	1.00	1.03	0.30	2.39	5.27	0.22	-	1.60	3.50	2.18	0.88	-	1.74	-	-	57.07
	HA	-	3.70	6.77	6.50	0.33	1.36	8.31	0.31	-	0.25	2.19	2.08	3.51	-	1.52	-	-	
fru.	A	2.25	1.79	2.06	1.68	0.20	2.96	5.53	0.15	-	1.19	3.59	2.76	2.23	0.11	2.55	0.18	-	78.97
	HA	0.58	2.25	6.02	4.23	0.66	1.19	19.12	0.06	-	3.11	3.56	1.18	1.24	0.07	4.44	1.41	-	

A adapted range, HA highly adapted range, C current climate, F future climate

A dash (-) represents the absence of distribution records on a soil. Species names are abbreviated as: exc.: *C. excisa*, lab: *C. laburnifolia*, pea: *C. pearsonii*, alt: *I. alternans*, het: *I. heterotricha*, mey: *I. meyeriana*, nig: *I. nigromontana*, dep: *L. depressa*, dif: *L. depressa*, exci: *L. excisa*, inc: *L. incana*, inf: *L. inflata*, pau: *L. pauciflora*, gla: *P. glaucescens*, ita: *S. italica*, tom: *C. tomentosum*, ser: *C. sericea*, fru: *L. frutescens*, Acrisols (AC), Arenosols1 (AR1), Arenosols2 (AR2), Arenosols3 (AR3), Cambisols (CM), Fluvisols (FL), Leptosols1 (LP1), Leptosols2 (LP2), Nitisols (NT), Phaezems (PH), Luvisols1 (PL1), Luvisols2 (PL2), Plinthosols1 (PT1), Plinthosols2 (PT2), Podzols (PZ), Regosols (R), Solonchaks (SC), Vertisols (VR)

experienced within water-limited agro-ecosystems, these species could provide higher edible biomass yields that could be collected and stored as livestock feed. The species selected are, therefore, also intended to be used as 'cut and carry' crops to be stored for when other forages in the veld become reduced or depleted. This is also the reason why spineless species were prioritised over spinescent species as this would simplify the cut and carry process, as well as the storage of these plants.

In water-limited environments, perennial species have an advantage over annual species due to a range of physiological adaptations. Perennial species have the ability to grow vegetatively for at least three growing seasons, unlike annual species that senesce after just one growing season after they have set seed (Pérez-Harguindeguy et al. 2013). Therefore, the perennial species can survive from one growing season to the next as mature plants, while the annual species would have to establish from seeds each year. Re-establishment from seed in water-limited agro-ecosystems is usually problematic, especially with legumes. Many legume species have been shown to display seed dormancy, primarily imposed on the seeds by the seed coat or testa (Werker et al. 1979; Bewley and Black 1994; Nowack et al. 2010; Bewley et al. 2013; Smýkal et al. 2014, Müller et al. 2017). In order for these seeds to establish and ensure forage for the following growing seasons, it would be imperative to first break the dormancy of the seeds before sowing to allow uniform, early germination and rapid seedling establishment, at the onset of the rainy season.

Unlike annual plants that escape drought or water-limited conditions as seeds, perennial plants have a greater diversity of physiological mechanisms by which they can tolerate and survive these dry conditions (Whalley and Davidson 1969; Harradine and Whalley 1978; Ludlow 1980; Hale and Orcutt 1987; Scott 2000; Pérez-Harguindeguy et al. 2013). In perennial plants, the mechanisms of adaptation to drought or water-limited conditions can be divided into four categories. The first category is drought tolerance where plants can withstand near air dryness but rapidly grow after being re-watered (Hale and Orcutt 1987; Scott 2000). The second category is drought tolerance with low plant water potential, a state where plants can endure low tissue water status without desiccation (Sinclair and Ludlow 1985; Hale and Orcutt 1987). The third category is drought tolerance with high plant water potential. Here plants can endure long periods without water while maintaining a high plant water status by reducing the

loss of water through transpiration (Sinclair and Ludlow 1985; Hale and Orcutt 1987). The fourth category is drought dormancy, where the shoots of the plant senesce when conditions are unfavourable but growth recommence when conditions become more favourable (Whalley and Davidson 1969; Harradine and Whalley 1978; Hale and Orcutt 1987).

#### Climate and soil adaptation

The 18 prioritised legume species were found to be limited by a range of different bioclimatic variables, and not all species were equally affected by the same variables. Approximately 39% of the species prioritised were found to be limited by temperature variables, 33% of the species were limited primarily by precipitation variables and 28% of the species were limited equally by temperature and precipitation variables. Each of these categories of species should be evaluated differently to determine the extent to which these variables could limit their use in water-limited agro-ecosystems. Apart from the bioclimatic variables limiting the species distributions, soils are also a major factor influencing species distributions (Nichols et al. 2007, Trytsman et al. 2016). In a broad evaluation of the potential of these legume species, identifying whether or not species naturally occur on a specific soil type provides a good indication of the extent of a species adaptation to those soils and whether those species can be used in agricultural systems with those soils (Nichols et al. 2007). Trytsman et al. (2016) studied the diversity and biogeographical patterns of legumes indigenous to southern Africa and found that soil pH as well as mean annual minimum temperatures were the main drivers for distinguishing among legume assemblages. These bioclimatic and edaphic limitations to the distributions of these legume species could, therefore, reduce the agronomic potential of many of these species, as this reduces the areas in which these species could be used. The 18 species that were prioritised in this study however, can tolerate a wide range of soil pH conditions ranging from as low as 5.5 to a maximum of 8.4 (Table 4) and soil phosphate concentrations ranging from 5 to 35 mg/kg (Trytsman 2013, Trytsman et al. 2016). Even so, the modelled ecological niches for the 18 native legume species in this study were found to be much wider than their current distributions. The wider modelled ecological niches, compared to the current distributions of the 18 legume species, raise the question as to why these

species are not filling their entire soil and climate niches. This may simply be because there are many factors, other than climate and soil conditions that influence the natural distribution of plant species. These factors include competition for limiting resources, herbivory, the mode of seed dispersal and the biological requirements for seed germination and seedling establishment (Bewley and Black 1994). If it were possible to include all of these variables into the model, it would likely result in an actual niche model with much smaller adaptation ranges. However, from an agricultural point of view, the actual ecological niche, i.e. variables other than climate and soil, may not be entirely relevant. This is due to many aspects of the agro-ecosystem being managed to suit the plant. For example, the mode of seed dispersal and biological requirements for seed germination and seedling establishment is controlled by the routine establishment and/or re-establishment of the species. Inter- and intra-specific competition can be controlled and managed to reduce the competition for limiting resources, and herbivores can be managed by fencing off planted areas (Bennet et al. 2011).

Some of the genera prioritised in this study are known to be good forages. For example, for some of the *Lessertia* species prioritised (*L. diffusa*, *L. excisa* and *L. incana*), evidence from Australian trials have indicated that these species are highly palatable and have shown some degree of grazing tolerance. They were also reported to become prostrate under high grazing pressure in trials done in Australia, which allows them to withstand continuous grazing pressure (Cocks 2001; Howieson et al. 2008; Gerding et al. 2013a; Gerding et al. 2013b). However, the high numbers of resident *Rhizobium* bacterial strains in the Australian soils that rapidly nodulate these *Lessertia* species but are non-fixing led to the discarding of *Lessertia* as an agricultural legume in Western Australia (Gerding et al. 2013a, 2013b; Gerding et al. 2014). Similarly, many *Indigofera* species that have been found to contain high protein concentrations, are able to respond well to small rainfall events and are drought, flood and saline tolerant (Skerman 1982; Hassen et al. 2004; Hassen et al. 2006a; Hassen et al. 2006b; Hassen et al. 2007, 2008, Snowball et al. 2013). Therefore, the *Indigofera* species prioritised in the present study (*I. meyeriana* and *I. nigromontana*) might have the same potential. Species of *Cullen* have also been evaluated and prioritised as potential forage crops in low-rainfall environments in Western Australia, suggesting that the *Cullen* species identified in the present study (*C. tomentosum*)

also merits further evaluation (Bennett et al. 2011; Bennett et al. 2012). Species in the genus *Crotalaria* have also been evaluated as forage crops elsewhere (Arias et al. 2003, Snowball et al. 2013, Naim et al. 2015). Therefore, *C. excisa*, *C. laburnifolia* and *C. pearsonii* identified and prioritised in this study should also be evaluated for their fodder potential. Furthermore, evidence has shown the importance of *Calobota sericea* (formerly known as *Lebeckia sericea*) as a potentially important dry season fodder species in the semi-arid rangelands of Namaqualand, South Africa (Samuels et al. 2015). In Namaqualand, *C. sericea* plays a very important role as a late dry season forage when other more palatable forage species have already been selectively removed from the rangelands. During the late dry season, dry leaves and pods of this plant provide forage that helps to fill the mid to late summer forage gap in these rangelands. Unfortunately, no information regarding the quality of the forage provided by *C. sericea* is available at this stage.

In conclusion, further research on the forage potential of these 18 prioritised legume species is needed. However, it is evident that native legume species from South Africa could play an important role in improving livestock production in currently water-limited environments in South Africa. Also, these species could become important forage crops under the predicted future hotter and drier bioclimatic conditions in South Africa. To do so, however, information regarding the germination potential, early seedling vigour, plant growth rate, responses to water and phosphate limitation, forage production and the quality of the forage produced by these plants need to be determined.

#### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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