

Persistence of tropical pasture legumes in the moderate rainfall sub-tropics of eastern Australia

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Received: 2 June 2026

Accepted: 11 August 2026

Published: 7 September 2026

Cite this: Peck GA *et al.* (2026) Persistence of tropical pasture legumes in the moderate rainfall sub-tropics of eastern Australia. *The Rangeland Journal* **48**, RJ26018. doi:10.1071/RJ26018

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ABSTRACT

Identifying pasture legume varieties that remain persistent and productive over the long-term has been a challenge in the moderate rainfall sub-tropics of eastern Australia. Although several legume cultivars considered adapted for clay soils were released in Australia in the mid-1990s in sub-tropical and tropical regions, graziers have reported that most failed to persist in established pastures. This study assessed the long-term persistence of pasture legume species with cultivars released in Australia. Forty-four old pasture evaluation sites were inspected, with an average age of 17.5 years after sowing. Thirteen legume species that had been sown at six or more sites were evaluated. Most species showed limited persistence, indicating that long-term adaptation across environments is uncommon. Only two species were widely persistent: (1) Caatinga stylo (*Stylosanthes seabrana*), which persisted at 78% of sites; and (2) *Desmanthus virgatus*, which persisted at 68% of site. These species demonstrated broad adaption to long-term pastures. Intermediate persistence (20–50% of sites) was recorded for *Desmanthus leptophyllus*, butterfly pea (*Clitoria ternatea*), leucaena (*Leucaena leucocephala*), shrubby stylo (*Stylosanthes scabra*), fine-stem stylo (*Stylosanthes guianensis* var. *intermedia*) and lotononis (*Listia bainesii*), suggesting adaptation to a narrower range of soil and climates. Other species, including burgundy bean (*Macroptilium bracteatum*), atro (*Macroptilium atropurpureum*), lucerne (*Medicago sativa*), Caribbean stylo (*Stylosanthes hamata*) and round-leaf cassia (*Chamaecrista rotundifolia*), persisted at few or no sites. The results show that most pasture legumes are not widely persistent in the region. Caatinga stylo and *D. virgatus* appear best suited to long-term pastures, while several other species may be useful in specific environments. This study highlights the importance of long-term evaluations for developing reliable recommendations for graziers.

Keywords: Brigalow Belt, *Chamaecrista*, *Clitoria*, *Desmanthus virgatus*, *Leucaena*, legume evaluation, *Listia*, *Macroptilium*, *Stylosanthes seabrana*.

Introduction

It has been challenging to find well-adapted and persistent legume species for the moderate rainfall sub-tropics of eastern Australia (Peck *et al.* 2011; Bell *et al.* 2016). Although pasture legumes have been released for tropical and sub-tropical climates, not all regions have identified legume cultivars that persist in commercial grazing systems (Bell *et al.* 2016; Smith *et al.* 2021).

The moderate rainfall sub-tropics of eastern Australia (approximately 500–700 mm mean annual rainfall) broadly align with the Brigalow Belt bioregion, and the E4 agro-climatic class (Fig. 1) (Thackway and Cresswell 1995; Hutchinson *et al.* 2005). The Brigalow Belt agro-climatic class (E4) is important for the Australian beef industry because it carries approximately 40% of Queensland's (10.6 million head), and 20% of Australia's (22 million head) beef cattle herd (ABS 2022).

The Brigalow Belt bioregion occupies approximately 36 million ha of eastern Australia, with approximately 80% located in Queensland (Fig. 1) (Thackway and Cresswell

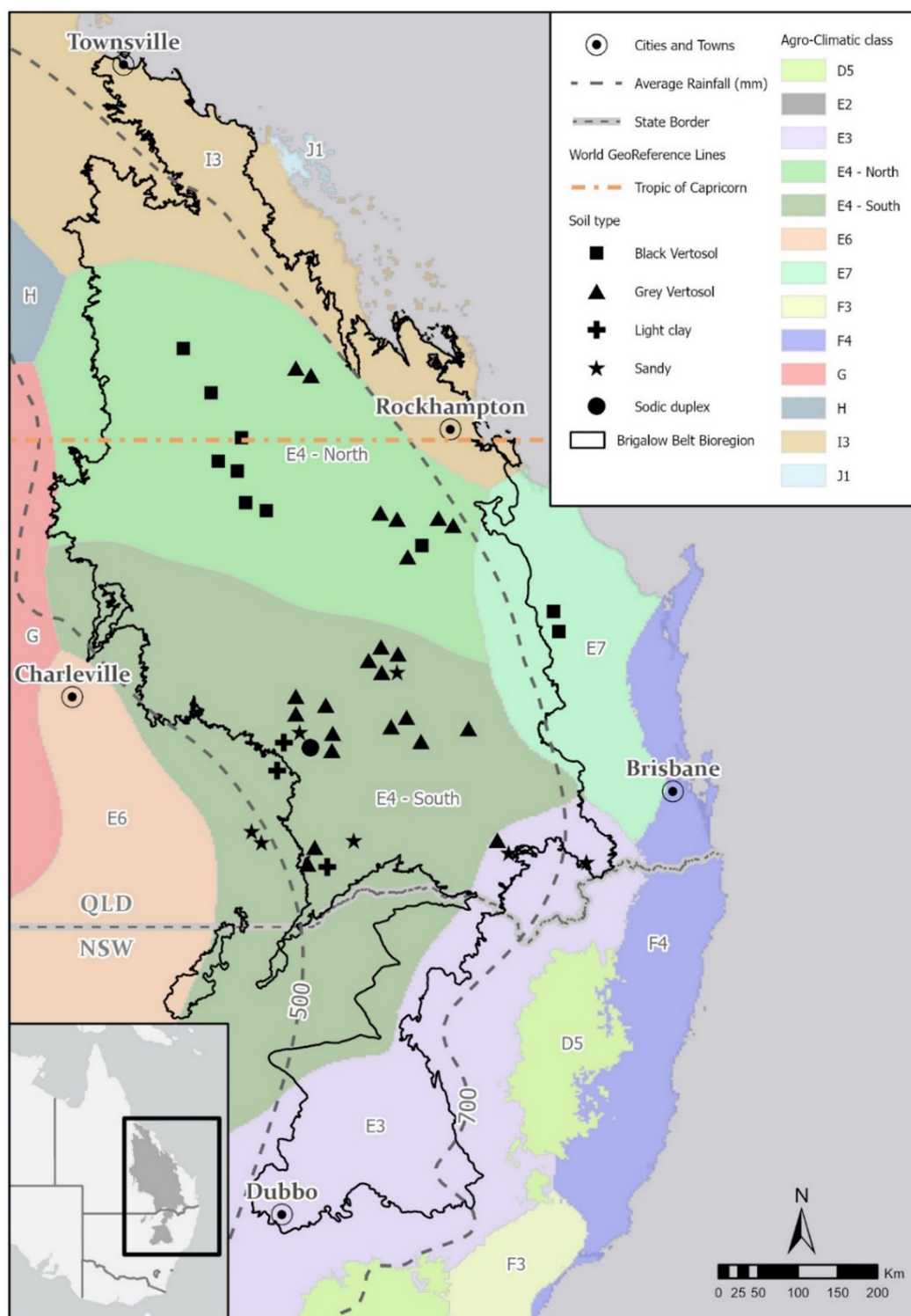


Fig. 1. Location of legume persistence trial sites compared to the geographic extent of the Brigalow Belt bioregion of eastern Australia (Thackway and Cresswell 1995), agro-climatic class modified from Hutchinson *et al.* (2005) and mean annual rainfall for the years 1911–2020 (BOM). Trial locations are shown by soil type markers. The E4 agro-climatic class (Brigalow Belt) was separated into north and south based on 20 average potential frost days per year for the period 1976–2005 (BOM 2008).

1995). The Brigalow Belt is characterised by an agro-climatic class with a sub-tropical climate with moisture deficits in all months of the year but is not arid, and by global standards has mild winters. However, frosts are common in southern latitudes, affecting the survival of tropically adapted plants (Hutchinson *et al.* 1992, Hutchinson *et al.* 2005). This bioregion includes a range of pasture communities including *Aristida-Bothriochloa*, Queensland bluegrass (*Dichanthium sericeum*), Black speargrass (*Heteropogon contortus*), Mitchell grass (*Astrebla spp.*), and Brigalow across a wide range of soil types (Tothill and Gillies 1992). Although the Brigalow Belt bioregion includes a wide range of land types including large areas of eucalypt woodlands on light textured soils, it is characterised by relatively fertile clay soils where the native vegetation was dominated or associated with Brigalow trees (*Acacia harpophylla* F.Muell. ex Benth.) (Queensland Herbarium 2018). Widespread clearing of both the eucalypt and Brigalow associated woodlands and forests, combined with relatively fertile soils and moderate rainfall, has supported extensive land development for agricultural production from modified native pastures, sown pastures and grain cropping (Partridge *et al.* 1994; Seabrook *et al.* 2006).

Although considered highly productive compared to most of northern Australia, the productivity of sown pastures in the Brigalow Belt bioregion declines by approximately 50% over the 5–10 years after sowing (Graham *et al.* 1981; Robbins *et al.* 1987; Radford *et al.* 2007). This decline is largely attributed to progressive depletion of plant-available nitrogen as it becomes immobilised in soil organic matter, a process commonly referred to as ‘pasture rundown’ (Graham *et al.* 1981; Myers and Robbins 1991; Robertson *et al.* 1997). The grass dominated native pastures that are typical of the climate zone are similarly inhibited by low nitrogen availability, leading to constrained pasture production and diet quality for grazing animals that results in lower livestock productivity (Peck *et al.* 2011).

Pasture legumes have been identified as the best option to increase productivity and profitability for both rundown sown grass pastures and native pastures in the Brigalow Belt, through biological nitrogen fixation leading to higher pasture yields and better feed quality for grazing livestock (Peck *et al.* 2011; Bowen and Chudleigh 2018). Approximately 70% of sown pastures in northern Australia were sown only with grass species (Walker and Weston 1990; Walker *et al.* 1997), and legumes have generally been unsuccessful in commercial pastures (Peck *et al.* 2011; Bell *et al.* 2016). Where legumes were included in early pasture sowings, most failed due to the use of poorly adapted cultivars, poor establishment and/or poor grazing management (Peck *et al.* 2011; Jones 2014).

Identifying legume species suitable for long-term pastures in the Brigalow Belt bioregion has been difficult

because the region’s sub-tropical climate constrains the productivity of both tropical and temperate legumes, and comparable environments are uncommon globally (Hutchinson *et al.* 2005). In response to early failures, research investment during the 1980s and 1990s led to the commercial release of several legumes from the *Stylosanthes*, *Desmanthus*, *Clitoria*, and *Macroptilium* genera during the 1990s (Bell *et al.* 2016; Smith *et al.* 2021). Evaluation trials indicated that *Desmanthus* spp. and Caatinga stylo (*Stylosanthes seabrana*) had good persistence and productivity on clay soils, leading to the release of commercial cultivars with Plant Breeders Rights granted in 1992 and 1996 respectively (Clem and Jones 1996; Edye and Maass 1997; Cook *et al.* 2020). Commercialising cultivars of Caatinga stylo and the *Desmanthus* spp. was considered innovative at the time because no cultivars had previously been released and species descriptions were published after commercialisation (Luckow 1993; Maass and Mannetje 2002). These species were promoted as hardy legumes capable of supporting long-term legume–grass pastures across a wider range of soils and climates, including the moderate rainfall sub-tropics. However, commercial performance has been variable in this region, with graziers frequently reporting poor establishment or persistence (Peck *et al.* 2010).

This discrepancy between research results and grazier experience suggests two possible explanations, either: (1) legume cultivars that are currently available are inadequately adapted for long-term persistence under commercial grazing; or (2) they are suitable, but current management practices need to be modified to adequately establish and maintain these legumes in grazed pastures.

The aim of this study was to evaluate the long-term persistence of commercially released pasture legumes across the range of soils and climates at 44 pasture evaluation or demonstration trials located throughout the Brigalow Belt climatic zone. Although numerous species and accessions were originally sown, this study focused on the 13 most widely sown species, with particular emphasis on Caatinga stylo and *Desmanthus* because these were relatively recent releases, intended to extend the range of environments where persistent pasture legumes could be established (Peck *et al.* 2011; Bell *et al.* 2016).

Materials and methods

Evaluation site descriptions, location, and climate

The evaluation sites varied in design, species sown, climate, and soil types (Table 1; see further description of sites in Supplementary material). Sites ranged in age from 5 years to 33 years after sowing (mean, 17.5 years). Only three sites were <10 years after sowing, 31 were >15

years after sowing, and four sites were >30 years after sowing. Trial types included small plots (10–50 m², $n = 15$), large plots (50–500 m², $n = 12$), demonstration/grazing trials (3–10 ha, $n = 10$), commercial paddocks (>15 ha, $n = 4$), and three sites had a combination of plot sizes or trial types (Table 1). Most sites had reverted to grazer management for >10 years.

The sites spanned northern E4-N ($n = 17$) and southern E4-S ($n = 22$) Brigalow Belt agro-climatic classes within Queensland, with five sites in cooler, frost prone E3 ($n = 3$) and higher rainfall E7 ($n = 2$) zones (Fig. 1). The mean annual rainfall across the sites ranges from 500 to 730 mm per year, with 70–81% occurring during the summer growing season (October to April) (Supplementary material). All northern E4-N sites were on cracking clay; southern sites included a broad range of soil types (Fig. 1 and Supplementary material).

Inspection of evaluation sites and assessment of legumes

Trials were located using published and archival records and consultation with late career and retired pasture scientists. Sites were inspected between May 2011 and May 2016 (Table 1) after sufficient pasture growth to allow identification of legume species. Some of the trials were inspected over multiple years; however, only the results from the first recording are described in this paper.

All legumes present at sites were recorded; however, only 13 species that have cultivars released in Australia and have been commercially sown in Queensland were assessed for long-term persistence (Table 2). The other sown legume species were not included in the assessment owing to low site representation, being unsuitable for long-term pastures (e.g. fodder crops), or lacking commercial cultivars.

Between two and over 400 legume accessions were sown at individual sites, although complete sowing lists were not available for all sites. Some sites had co-located trials in addition to the main trial, and at some sites, some plots that failed to establish or maintain a legume population were subsequently sown to a different species that was not recorded in the original sowing list; however all legumes present at the sites was recorded.

Assessment of persistence

Legume patch size, plant density (plants m⁻²), population structure, health, and vigour were recorded and compared to the original trial design to determine whether legumes were persisting and spreading from where they were sown. Plant density and spread were rated on a scale of 0–6 (Table 3). Early post-sowing population data were considered where available. For sites without establishment data, it was assumed that an adequate legume population was established to enable long-term persistence (>4 adult

plants m⁻² for most of the species assessed), because failed plots were normally resown to achieve an acceptable plant density.

For most legumes, a persistence index was calculated as plant density $\times$ spread; although for leucaena, only density was used owing to its tree growth habit. Persistence indices were categorised into five levels (Table 4).

Assessing factors that may affect legume persistence

Nine factors that may influence long-term legume persistence were used to describe each site:

1. Soil type. Trial sites were categorised into broad soil descriptions based on the Australian Soil Classification (Isbell 2016). Soil categories were grey Vertosols ($n = 23$), black Vertosols ($n = 10$), light clays ($n = 3$), sandy soils ($n = 7$), and a sodic duplex ($n = 1$) (Table 1). The Vertosol soil groupings include Vertosol and Dermosol soils with vertic properties. The light clay soils included Dermosols and Sodosols; sandy soils include Kandosol, Tenosol, Arenosol, and duplex soils with deep (>50 cm) sandy textured A horizons (i.e. Kurosol, Chromosol, or Sodosol); the sodic duplex soil had a shallow A horizon (20 cm deep with a strongly bleached A2 horizon) and strongly dispersive sub-soil.
2. Agro-climatic classification (Hutchinson *et al.* 1992, Hutchinson *et al.* 2005).
3. Mean annual rainfall for years 1889–2016, SILO database (Jeffrey *et al.* 2001).
4. Mean summer growing season rainfall (October–April inclusive), for years 1889–2016, SILO database (Jeffrey *et al.* 2001).
5. Years since sowing.
6. Grazing pressure on grass.
7. Grazing pressure on legumes.
8. Grass competition.
9. Land condition (Aisthorpe *et al.* 2004).

The method used for agro-climatic classification, grazing pressure, and grass competition are described in the following sections.

Agro-climatic classification

The agro-climatic classification of Hutchinson *et al.* (1992) was used to assess climate impacts on legume persistence because it is based on the effect of climate on plant growth and is therefore closely aligned with the agronomic adaptation of crops and pastures (Hutchinson *et al.* 2005).

The main agroclimatic class of the Brigalow Belt bioregion (E4) was modified by separating into northern and southern regions based on an average of 20 potential frost days per year (reference years 1976–2005, (BOM 2008)); the northern zone (E4-N) averages <20 potential frost

Table 1. Description of location, age (years post sowing), plot size, legume accessions sown, rainfall, and soil type of the trial sites assessed for legume persistence.

Site		Location (Decimal Degrees)		Trial age (years)		Plot size ^A (m ²)	Accessions sown	Soil type ^D	Reference
No.	Name	South	East	Sown	Assess		Species ^B	No. ^C	
1	Bringalilly clay	28.1	151.2	1978–81	2011	4	Dv, Ssc, Sh, Sg, Ct, Mb, Ma, Cr, Lb, Ll.	394	Grey Vertosol
2	Bringalilly sand	28.1	151.2	1978–81	2011	4	Dv, Ssc, Sh, Sg, Ct, Mb, Ma, Cr, Lb, Ll.	394	Sandy
3	Chelmer 1	28.2	149.0	2004	2011	500	Sse.	2	Grey Vertosol
4	Chelmer 2	28.2	149.0	2000	2011	500	Sse.	2	Grey Vertosol
5	Dunbar	28.3	149.0	2006	2011	100 ha	Sse, Ssc.	3	Light clay
6	Mulga View farming systems	28.0	148.3	2001	2011	360	Sse, Ssc, Mb, Ms.	5	Sandy
7	Mulga view pasture	28.0	148.3	1986	2011	6	Dv, Ssc, Ct, Ma, Ms, Cr, Ll.	34	Sandy
8	Ballaroo	27.2	148.6	1993–94	2011	25 m ² , 3 ha	Dv, Dl, Sse, Ssc.	15	Light clay
9	Holyrood	26.8	148.8	1988–94	2011	4–100	Dv, Dl, Sse, Ssc, Sh, Sg, Ct, Ma, Ms, Cr, Lb.	>400	Light clay
10	Ardenrive	26.8	148.8	1996–97	2011	4 ha	Dv, Dl, Sse, Ssc.	6	Sandy
11	Banoona PDS	26.9	149.1	1995	2011	1 ha, 5 ha	Dv, Dl, Sse, Ct.	6	Grey Vertosol
12	Banoona paddock	26.9	149.1	1996	2011	50 ha	Dv, Dl.	3	Grey Vertosol
13	Roma Research Station	26.6	148.8	1996	2011	2	Dv, Dl.	NR ^E	Grey Vertosol
14	Fairlands PDS	26.5	149.1	1995	2011	4 ha	Dv, Dl, Sse, Ct.	6	Grey Vertosol
15	Sylvan Hills sand	26.0	149.8	1979–81	2011	4	Dv, Ssc, Sh, Sg, Ct, Mb, Ma, Cr, Lb, Ll.	394	Sandy
16	Sylvan Hills clay	26.0	149.8	1979–81	2011	4	Dv, Ssc, Sh, Sg, Ct, Mb, Ma, Cr, Lb, Ll.	394	Grey Vertosol
17	Sylvan Hills paddock	26.0	149.8	1996	2011	2 ha	Dv, Dl.	3	Grey Vertosol
18	Brian Pastures Mt Bambling	25.7	151.8	1998	2011	2.5 ha	Sse, Ct, Mb.	7	Black Vertosol
19	Brian Pastures Mt Brian	25.7	151.7	1996	2011	3.2 ha	Dv, Dl, Ssc, Ll.	7	Black Vertosol

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Table 1. (Continued)

Site		Location (Decimal Degrees)		Trial age (years)		Plot size ^A (m ²)	Accessions sown	Soil type ^D	Reference
No.	Name	South	East	Sown	Assess		Species ^B	No. ^C	
20	Kapalee Plots	24.4	150.4	1994	2011	200	Dv, Dl, Sse, Ssc, Sh, Ct, Mb, Ma, Ms, Ll.	16	Grey Vertosol Clem and Jones (1996)
21	Kapalee grazing demo	24.4	150.4	1994	2011	10 ha	Dv, Dl.	3	Grey Vertosol Clem and Jones (1996)
22	Thisit paddock	24.4	149.9	1997	2011	2 ha, 14 ha	Dv, Dl, Sse.	5	Grey Vertosol R. Clem, pers. comm.
23	Thisit grazing demo	24.4	149.9	1997	2011	10 ha	Sse.	2	Grey Vertosol Walker (1998) ; Peck et al. (2017a)
24	Valencia	23.0	147.8	1997	2011	50	Dv, Dl, Sse, Ct, Mb, Ma, Ms.	35	Black Vertosol Pengelly and Conway (1998) ; Pengelly and Lloyd (2001)
25	Mutation	22.5	147.5	1994	2011	200	Dv, Dl, Sse, Ssc, Sh, Ct, Mb, Ma, Ms, Ll.	16	Black Vertosol Clem and Jones (1996)
26	Emerald Research Station	23.5	148.2	1992–96	2011	25	Dv, Dl, Sse, Ssc, Ct, Mb, Ma, Ms.	152	Black Vertosol Clem and Jones (1996) ; Pengelly and Lloyd (2001) .
27	Juanita	23.8	148.1	1996–97	2011	10	Dv, Dl, Sse, Ct, Mb, Ma, Ms.	63	Black Vertosol Pengelly and Conway (1998) ; Pengelly and Lloyd (2001)
28	Stoneybrook PDS	23.8	148.0	1998	2011	10 ha	Sse.	2	Black Vertosol Walker (1998)
29	Birrong stylo	24.2	148.3	1991–94	2011	20	Sse, Ssc, Sh, Sg.	15	Black Vertosol Anonymous (1999)
30	Birrong LCS	24.2	148.3	1994	2011	200	Dv, Dl, Sse, Ssc, Sh, Ct, Mb, Ma, Ms, Ll.	16	Black Vertosol Clem and Jones (1996)
31	Rangeview	24.7	150.1	1994	2011	200	Dv, Dl, Sse, Ssc, Sh, Ct, Mb, Ma, Ms, Ll.	16	Black Vertosol Clem and Jones (1996)
32	Kookaburra grazing demo	25.9	149.8	1993	2011	10 ha	Dv, Dl.	3	Grey Vertosol Clem and Jones (1996)
33	Kookaburra plots	25.9	149.8	1994	2011	100	Dv, Dl, Sse, Ssc, Sh, Ct, Mb, Ma, Ms, Ll.	16	Grey Vertosol Clem and Jones (1996)
34	Rolf Park plots	22.7	148.8	1995	2011	200	Dv, Dl, Sse, Ssc, Sh, Ct, Mb, Ma, Ms, Ll.	23	Grey Vertosol Clem and Jones (1996)
35	Rolf Park grazing demo	22.7	148.8	1995	2011	10 ha	Dv, Dl.	3	Grey Vertosol Clem and Jones (1996)
36	Sunshine Plains	24.8	150.0	1998	2011	10	Dv, Dl, Sse, Ct, Mb, Ma.	>70	Grey Vertosol B. Pengelly, pers. comm.
37	Morgan Park	28.3	152.1	1985	2013	4	Ssc, Cr, Lb.	4	Sandy R. Silcock, pers. comm.
38	Ula Ula	28.0	149.4	1985	2013	6	Dv, Ssc, Ct, Ma, Ms, Cr, Ll.	34	Sandy Silcock et al. (2014)

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Table 1. (Continued)

Site		Location (Decimal Degrees)		Trial age (years)		Plot size ^A (m ²)	Accessions sown	Soil type ^D	Reference
No.	Name	South	East	Sown	Assess		Species ^B	No. ^C	
39	Lyndon Caves	26.8	148.9	1986	2013	6	Dv, Ssc, Ct, Ma, Ms, Cr, Ll.	34	Sodic duplex
40	Norton	26.4	148.8	1986	2013	6	Dv, Ssc, Ct, Ma, Ms, Cr, Ll.	34	Grey Vertosol
41	Ellenvale	26.7	150.7	1995	2016	200	Dv, Dl, Sse, Ssc, Sh, Ct, Mb, Ma, Ms, Ll.	23	Grey Vertosol
42	Bidson paddock	26.7	149.8	2008	2016	20 ha	Dv, Sse, Ll.	4	Grey Vertosol
43	Bidson trials	26.7	149.9	2001	2016	10–250	Dv, Dl, Ct, Mb, Ms.	28	Grey Vertosol
44	Toston	26.9	150.2	1999	2016	10	Dv, Dl, Ct, Mb, Ll.	>200	Grey Vertosol

^APlot size is listed as square metres unless stated in hectares.

^BThe species assessed for persistence are listed, additional species (grasses and legumes) were sown at many of the sites. Species abbreviations: Cr: *Chamaecrista rotundifolia*; Ct: *Clitoria ternatea*; Dl: *Desmanthus leptophyllus*; Dv: *Desmanthus virgatus*; Lb: *Lotononis bainesii*; Ll: *Leucaena leucocephala*; Ma: *Macroptilium atropurpureum*; Mb: *Macroptilium bracteatum*; Ms: *Medicago sativa*; Sg: *Stylosanthes guianensis* var. *intermedia*; Sh: *Stylosanthes hamata*; Ssc: *Stylosanthes scabra*; Sse: *Stylosanthes seabrana*.

^CNumber of legume accessions sown. Accessions of grass were also sown at many of the sites.

^DSoil type is based on the Australian Soils Classification (Isbell and NCST 2016). The 'Light clay' soil type includes Dermosols and Sodosols with a clay-loam surface. The 'Sandy soil' soil grouping includes Kandosols, duplex and alluvial soils.

^ENR: no records.

days per year, the southern zone (E4-S) averages >20 potential frost days per year (Fig. 1). The separation line approximates the southern limit of some of the tropically adapted legume cultivars.

Grazing pressure and grass competition ratings

Grazing pressure and competition were rated on six-step scales based primarily on field observations at the time of assessment but also considered historical records and observations from scientists who had previously managed the trials and graziers who were managing the sites at the time of inspection (Table 5). Grazing pressure was rated separately for the grass and legume, because at some sites livestock were preferentially grazing the legumes at time of assessment, although at some sites livestock were preferentially grazing grass when the sites were inspected.

Grass competition ratings were based on the species and biomass of grasses that were dominant at the site (Table 5).

Most sites either had open gates or fences were no longer stock proof. Therefore, site condition generally reflected the surrounding paddock, with 24 sites rated as having moderate or moderate-low grazing pressure on the legumes. Twelve sites were preferentially (and therefore heavily) grazed compared to surrounding paddocks, with the legumes having a high grazing pressure rating. Four

sites (6, 13, 26, 27) had no grazing by livestock, and four sites (11, 19, 25, 31) had infrequent grazing by livestock (low grazing pressure rating) based on records from the scientists who had previously managed the trial sites and discussions with the grazer about how they manage the site. Three of the infrequently grazed trials were currently enclosed in paddocks used for grain cropping (11, 25, 31), and one trial was in a 'quarantine' paddock being managed to control an exotic weed (19).

Statistical methods

The effects of the nine listed discrete and continuous factors that may affect legume persistence, including their interactions, on individual rating scales (persistence and plant density), along with their product (persistence index), were investigated with general linear models (GLMs), using Genstat (VSN International 2024). Residuals approximated normal distributions so no transformations were needed. Significant factors ($P < 0.05$) were further examined using *post-hoc* least significant difference tests between the factor-level means.

Legumes absent at all sites (lucerne, Caribbean stylo, round-leaf cassia) or present at very few sites (lotononis, fine-stem stylo) were excluded from the statistical analysis. The lack of long-term persistence of these

Table 2. Legume species that were assessed for long-term persistence and the number of sites where they were sown.

Species	Common name	Sites
<i>Chamaecrista rotundifolia</i> (Pers.) Greene	Round-leaf cassia	10
<i>Clitoria ternatea</i> L.	Butterfly pea	25
<i>Desmanthus leptophyllus</i> Kunth	Desmanthus	26
<i>Desmanthus virgatus</i> L. Willd.	Desmanthus	35
<i>Leucaena leucocephala</i> (Lam.) De Wit	Leucaena	18
<i>Listia bainesii</i> (Baker) B.-E. van Wyk & Boatwr.	Lotononis	6
<i>Macroptilium atropurpureum</i> (DC.) Urb	Atro, Siratro	20
<i>Macroptilium bracteatum</i> (Nees & Mart.) Marechal & Baudet	Burgundy bean	19
<i>Medicago sativa</i> L.	Lucerne	17
<i>Stylosanthes guianensis</i> (Aubl.) Sw. var. <i>intermedia</i> (Vogel) Hassl.	Fine-stem stylo	7
<i>Stylosanthes hamata</i> (L.) Taub	Caribbean stylo	13
<i>Stylosanthes scabra</i> Vogel	Shrubby stylo	24
<i>Stylosanthes seabrana</i> B.L. Maass & 't Mannetje	Caatinga stylo	27

species was described by the percentage of sites where they persisted.

Results

Legume persistence: species

Legume species persistence varied substantially (Table 6). Caatinga stylo (*S. seabrana*) and *D. virgatus* were the most persistent species. Caatinga stylo had a mean persistence index of 17.1 and moderate to very high persistence at 78% of sites where sown. *D. virgatus* had a mean persistence index of 14.8 and moderate to very high persistence at 68% of sites. Other species ranged from persisting at no sites through to moderate to very high persistence ratings at 46% of sites with (Table 6)

Legume persistence: soil type

Persistence of most legume species varied with soil type (Table 7). *D. virgatus*, leucaena (*L. leucocephala*) and

butterfly pea (*C. ternatea*) had higher persistence on clay soils. *D. virgatus* had lower persistence on black vertosols than on grey vertosols or light clays. Leucaena and butterfly pea had higher persistence on black vertosols than on other soils.

Caatinga stylo (*S. seabrana*) had high persistence across all soil types with no significant differences between soil types. Shrubby stylo (*S. scabra*) had higher persistence on sandy soils than on clay soils.

Persistence of *D. leptophyllus* did not differ significantly among soil types ($P > 0.05$), although higher persistence was recorded on grey vertosols ($P = 0.09$).

Other legume species persisted at an insufficient number of sites to demonstrate adaptation to different soil types.

Legume persistence: agro-climatic class

Persistence in each agro-climatic class is in Table 8 for legume species that persisted at $> 25\%$ of sites where they were sown. There were insufficient sites in the E7 and E3 agro-climatic classes to allow for meaningful interpretation; therefore, discussion focuses on the E4-N and E4-S agro-climatic classifications.

Caatinga stylo and *D. virgatus* had high persistence in both E4-N and E4-S. Butterfly pea and leucaena had higher persistence in E4-North than in E4-South. Shrubby stylo had moderate persistence in E4-S but did not persist in E4-North where it was only sown on vertosol soils.

Legume persistence: other factors

GLMs and classification and regression trees identified few relationships between legume persistence and the seven additional site factors assessed (Table 9). The GLMs presented include slopes describing the relationship for the factor and axis intersects for the soil type effect (Figs 2–4).

Persistence of *D. leptophyllus* was positively associated with mean summer growing-season rainfall and declined with years since sowing (Figs 2 and 3) as well as a correlation with soil type (Table 7). Relationships were not plotted for light clay and sandy soils due to the limited number of sites with these soil types.

Leucaena plant density declined with increasing years since sowing (Fig. 4). Most observations were from grey vertosol sites, with fewer observations for black vertosol and sandy soil sites. A relationship is shown for grey Vertosol results, but not for black Vertosol and sandy soils because there was a limited range of years post sowing for these soil types.

Persistence of atro was statistically associated with grazing pressure; however, atro had moderate or greater persistence at only 10% of sites where sown.

Table 3. Plant density and degree of spread ratings.

Score	Rating	Plant density description ^A	Degree of spread description
0	No plants found	No plants found	No plants found
1	Extremely low	Extremely low plant density. A few isolated plants found.	No spread
2	Very low	Very low plant density; i.e. significantly fewer plants than what was originally in the trial or paddock.	Isolated plants found close to original plot.
3	Low	Low plant density. Decline in legume density relative to what was established in the original trial. Low plant number when assessed across replicates at trial sites.	Plants or patches found but close to original plot and/or with isolated plants or very small patches (few plants together) elsewhere.
4	Moderate	Moderate plant density. Slight increase in legume density. Moderate plant numbers when assessed across the trial site replicates or paddock. For <i>Leucaena</i> , there was enough plant density that it would be likely to increase animal production (compared to grass only).	High plant numbers at a moderate (20–30 m) distance from original plots.
5	High	High plant density. Moderate increase in legume density compared to what was originally established. High plant numbers when assessed across the trial site replicates or paddock. For <i>Leucaena</i> , there were approximately as many plants as originally established.	High plants numbers at 30–100 m from original plot.
6	Very high	Very high plant density. Large increase in legume density compared to what was originally established. Very high plant numbers when assessed across the trial site replicates or paddock. For <i>Leucaena</i> , there was an increase in plant density and/or recruitment outside of original plots or rows in paddocks.	High plant numbers at a moderate distance 50m + from original plots but patches of plants found at greater distance e.g. >100 m away from the original plot.

^AAssessed within the area originally sown. For sites that did not have plant density data from the original trial, it was assumed that >4 plants/m² was achieved during the establishment phase.

Table 4. Description of legume persistence ratings. Legume persistence ratings only considered plant density for *leucaena*; for other legume species, the persistence ratings were calculated from both the plant density near the original plots and degree of spread.

Persistence rating	<i>Leucaena</i> : plant density rating	Other legumes: persistence index ^A	Description/interpretation
Nil	0–2	≤2	Very few or no plants. Not persisting.
Low	3	3–6	Low plants numbers with very little spread. Unlikely to persist in the long term.
Moderate	4	7–12	Uncertain if legume is persisting in the long-term. Legume could be thickening or declining in the pasture. Legume percentage at time of recording likely to supply only small animal production benefits.
High	5	13–19	Persisting and some spread into surrounding pasture. Likely to provide animal production benefits. For <i>Leucaena</i> , maintaining high plant density.
Very high	6	20–36	Persisting and spreading. Highly suited to climate, soil and grazing management of the site.

^APersistence index = plant density score × degree of spread score. Plant density and degree of spread rating scores are described in Table 2.

Discussion

Variation in legume persistence

Long-term persistence varied considerably across the 13 legume species assessed. Species rated as having moderate to very high persistence maintained sufficient plant density to contribute useful forage for livestock, whereas those rated as low or not persistent were

unlikely to provide sustained livestock productivity benefits. Although hard-seeded legumes may persist as seed in the soil and reappear after disturbance or favourable seasons, this study focused on legumes capable of maintaining productive plant populations in long-term grazed pastures which requires sufficient and regular recruitment and/or perennating plants.

Of the 13 species assessed, only two, *Caatinga stylo* and *Desmanthus virgatus*, were widely persistent, with

Table 5. Grazing pressure and grass competition ratings.

Rating	Grazing pressure description	Grass competition description
Nil	Either no grazing or very occasional grazing, e.g. located within a cultivated paddock with some grazing of stubble occasionally.	Negligible grass.
Low	Grazing only at some times; e.g. grazing of stubble most years.	Grass species with low DM ^A production, gaps in the pasture and low ground cover; e.g. no grass sown with limited if any colonisation by grass.
Medium-Low	Low year-round grazing pressure, or moderate grazing pressure but frequently spelled (e.g. trial site fenced and occasionally opened to grazing).	Some grass competition, but less than most grazed grass/legume pastures; e.g. sites planted to legume only and the grass has not fully invaded the trial site, grass species with lower DM ^A production potential.
Medium	Grazing controlled to levels similar to recommended practices or district averages.	Well established grasses with moderate to high grazing pressure. Or pastures with moderate pasture and ground cover.
High	Heavy grazing of surrounding paddock with the trial site being similar. Or preferential grazing of trial site due to site not having stock proof fences or gate open most of the time. Short grass and legume.	Well established grasses with high DM ^A production species dominating the site.
Very High	Not applicable.	Well established grasses with very high DM ^A production dominating the site with little or no grazing. Or high fertility soils with very high grass DM ^A production.

^ADM: Dry Matter (kg ha⁻¹).**Table 6.** Long-term persistence of legume species at evaluation sites across the moderate rainfall sub-tropics of eastern Australia. The trial sites had an average time since sowing of 17.5 years. Sites were geographically spread across the Brigalow Belt bioregion.

Species	Number of sites sown	Persistence rating ^A (% of sites)					Mean persistence index ^B
		Not (≤ 2) ^C	Low (3–6) ^C	Moderate (7–12) ^C	High (13–19) ^C	Very high (≥ 20) ^C	
<i>Stylosanthes seabra</i>	27	7%	15%	30%	0%	48%	17.1
<i>Desmanthus virgatus</i>	35	26%	6%	14%	17%	37%	14.8
<i>Desmanthus leptophyllus</i>	26	27%	27%	31%	4%	12%	8.0
<i>Leucaena leucocephala</i>	18	61%	6%	6%	22%	6%	1.9 ^D
<i>Clitoria ternatea</i>	25	68%	4%	4%	8%	16%	5.8
<i>Stylosanthes scabra</i>	24	75%	4%	4%	0%	17%	5.6
<i>Listia bainesii</i>	6	67%	0%	17%	0%	17%	5.3
<i>Stylosanthes guianensis</i> var. <i>intermedia</i>	7	71%	0%	14%	0%	14%	4.6
<i>Macroptilium atropurpureum</i>	20	80%	10%	5%	5%	0%	1.8
<i>Macroptilium bracteatum</i>	19	74%	16%	5%	5%	0%	1.7
<i>Medicago sativa</i>	17	100%	0%	0%	0%	0%	0.0
<i>Stylosanthes hamata</i>	13	100%	0%	0%	0%	0%	0.0
<i>Chamaecrista rotundifolia</i>	10	100%	0%	0%	0%	0%	0.0

^APersistence of legumes was classified as described in Table 4 and incorporated plant density and spread (Table 3).^BLegume species are arranged in descending order of mean persistence index across sites, except for leucaena which was based only on legume density.^CThe persistence index ranges used to classify legume persistence ratings at sites are shown in brackets.^DLegume density rating is shown for leucaena. Leucaena was compared and ranked to other species based on the percentage of sites where it persisted.

moderate or greater persistence at >60% of sites. *D. leptophyllus* showed moderate persistence (persisted at 46% of sites). *Leucaena*, butterfly pea, and shrubby stylo persisted at a narrower range of sites (20–40%

of sites), based on soil type and/or climate zone. *Lotononis* and fine-stem stylo persisted at few sites. *Atro*, burgundy bean, lucerne, Caribbean stylo, and round-leaf cassia showed little or no persistence at any sites.

Table 7. Long-term persistence of legume species on different soil types. The trial sites had an average age of 17.5 years after sowing. Different letters indicate significant differences ($P < 0.05$) within a species.

Species	No. sites sown ^c	Average persistence index ^b					P-value
		Black vertosol (10 ^a)	Grey Vertosol (23 ^a)	Light clay (3 ^a)	Sandy (7 ^a)	Average s.e.	
<i>Stylosanthes seabrana</i>	27	18.9a	16.5a	18.0a	12.0a	5.54	0.884
<i>Desmanthus virgatus</i>	35	11.4b	19.7c	22.0bc	0a	3.98	<0.001
<i>Desmanthus leptophyllus</i>	26	4.4a	10.9a	2.0a	0a	4.10	0.094
<i>Leucaena leucocephala</i>	18	5.3b	1.6a		0a	0.68	<0.001
<i>Clitoria ternatea</i>	25	17.6b	1.9a	0.0a	0a	3.56	<0.001
<i>Stylosanthes scabra</i>	24	0.2a	0a	9.3ab	15.1b	3.80	0.013
<i>Listia bainesii</i> ^d	6		0	0	10.7		
<i>Stylosanthes guianensis</i> var. <i>intermedia</i> ^d	7	0	0	0	10.7		
<i>Macroptilium atropurpureum</i>	20	5.8b	0a	0a	0a	2.08	0.044
<i>Macroptilium bracteatum</i>	19	2.6a	0a		5a	1.81	0.197
<i>Medicago sativa</i> ^d	17	0	0	0	0		
<i>Stylosanthes hamata</i> ^d	13	0	0	0	0		
<i>Chamaecrista rotundifolia</i> ^d	10		0	0	0		

^aNumber of sites with this soil type. The soil types with less sites have less replicates in the statistical analysis and therefore a higher individual s.e. that is accounted for by the least significant difference analysis.

^bPersistence index is shown for all legumes other than leucaena. Leucaena plant density ratings are shown. Leucaena persistence only considered legume density because leucaena plants can perennate for decades and recommended grazing management is to limit seed set and recruitment.

^cOne site was excluded from this analysis. Site 39 (Lyndon Caves) was excluded from this analysis because it was the only shallow sodic duplex soil and no legume species persisted.

^dExcluded from statistical analysis as they did not persist at any sites or very few sites.

Widely persistent species

Caatinga stylo

Caatinga stylo was the most consistently persistent species and persisted on a wide range of soils (i.e. cracking clays, light clays and sandy soils). Visual observations suggested high biomass production and greater leaf retention through autumn and into winter compared with *D. virgatus*. Persistence was not strongly associated with soil type, indicating broad adaptation and supporting the results of Edye *et al.* (1998). Long-term survival of Caatinga stylo at sites (23, 32, and 33) with low soil phosphorus (3–7 mg kg⁻¹ Colwell P), which were used for other studies, suggests tolerance to low fertility conditions (Colwell 1963; Peck *et al.* 2017a).

Desmanthus virgatus

D. virgatus was widely persistent on clay soils but not sandy soils (Table 7); however, it was less persistence at Black Vertosol sites that warrants further investigation because it is considered suited to alkaline clay soils (Cook *et al.* 2020). *D. virgatus* persisted at some sites (32, 33) with low soil phosphorus (3–5 mg kg⁻¹ Colwell P) that were used for other studies, which suggests tolerance to low fertility soils (Colwell 1963; Peck *et al.* 2017a).

D. virgatus had high densities of small plants at many sites (indicative densities and height: >40 perennating plants m⁻² and 5–20 cm high), with low legume biomass (kg ha⁻¹) and poorer leaf retention at the time of recording than the stylos or larger statured *Desmanthus* species (<10 plants m⁻² and 30–80 cm high). The most widely sown cultivar of *D. virgatus* was ‘Marc’, a small-statured accession (generally 30–60 cm high) with high seed production; however other commercial varieties that can grow as larger plants (e.g. JCU2 can grow as a 50–80 cm sward in the sub-tropics) also seem to produce a high density of small plants with poor leaf retention after they have been established for >10 years (Peck *et al.* 2022b). Observations at several sites suggest that alternative *Desmanthus* accessions may offer improved biomass production and leaf retention.

D. virgatus was dominant with little grass in the plots where it was originally sown at several sites. Management and grass species selection is likely to be important to maintain optimum grass:legume ratios.

Traits of the widely persistent species

D. virgatus and Caatinga stylo have similar traits that may contribute to their widespread persistence in the moderate rainfall sub-tropics as well as some differences. Cultivars released in Australia for both *D. virgatus* and Caatinga

Table 8. Long-term persistence of legume species^A in each agro-climatic class (Hutchinson *et al.* 2005).

Agro-climatic class	<i>Desmanthus virgatus</i>			<i>Desmanthus leptophyllus</i>			<i>Stylosanthes seabrana</i>			<i>Stylosanthes scabra</i>			<i>Clitoria ternatea</i>			<i>Leucaena leucocephala</i>		
Agro-climatic class	Persistence index ^B	s.e.	Sites ^C	Persistence index	s.e.	Sites	Persistence index	s.e.	Sites	Persistence index	s.e.	Sites	Persistence index	s.e.	Sites	Plant density ^D	s.e.	Sites
E3	4.5	8.1	2			0			0	16.0	5.8	3	0.0	4.8	2	0.0	1.3	2
E4-N	16.4	3.3	12	9.6	2.2	12	17.7	3.2	13	0.1	3.8	7	15.1	2.2	9	4.2	0.8	5
E4-S ^E	15.3	2.6	19	6.5	2.2	13	15.9	3.2	13	7.2	2.9	12	0.2	2.0	12	1.0	0.6	9
E7	20.0	11.5	1	9.0	7.8	1	25.0	11.5	1	0.0	10.1	1	8.0	6.9	1	5.0	1.8	1
P-value	0.568			0.62			0.727			0.157			<0.001			0.015		
Total			34			26			27			23			24			17

^AOnly legumes that were sown at >15 sites and persistent at >25% of sites are included in this analysis.^BPersistence index (described in Table 4).^CNumber of sites sown in each climate zone.^DLegume density rating is shown for leucaena.^EOne site was excluded from this analysis. Site 39 (Lyndon Caves) was excluded from this analysis because it was the only shallow sodic duplex soil and no legume species persisted.

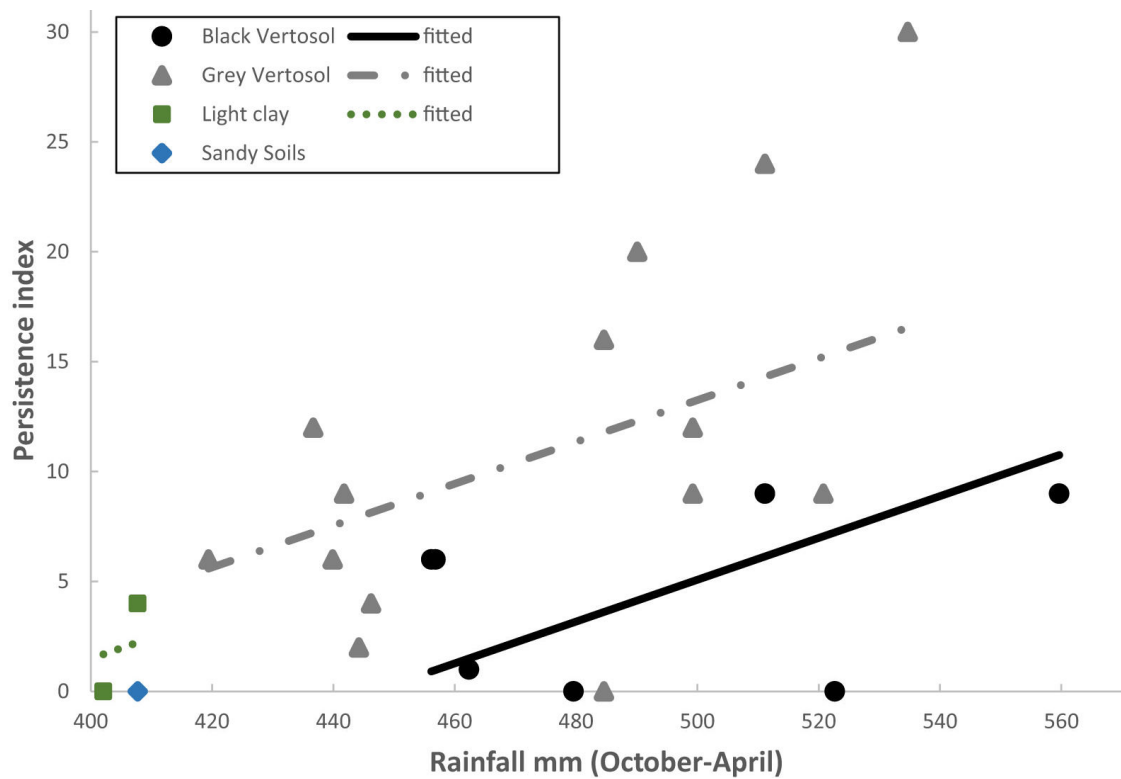


Fig. 2. Persistence of *Desmanthus leptophyllus* compared to mean summer growing season rainfall and soil type across the 26 sites where sown ($F_{4,21} = 4.25$, $P = 0.011$, $R^2 = 34.2\%$, slopes $P = 0.047$, soil types $P = 0.012$, the linear model includes separate soil type intersects).

Table 9. Legume species that had a correlation between long term persistence and the other assessed explanatory factors used to describe the trial sites.

Factor	Species	Slope	s.e.	P-value
Mean annual rainfall.	All	–	–	>0.05
Mean summer growing season rainfall (October–April)	<i>Desmanthus leptophyllus</i>	0.095	0.035	0.012
Years since sowing	<i>Desmanthus leptophyllus</i>	–2.06	0.80	0.018
	<i>Leucaena leucocephala</i>	–0.153	0.057	0.018
Grazing pressure on grass	All	–	–	>0.05
Grazing pressure on legumes ^A	<i>Macroptilium atropurpureum</i>	–10.5	2.4	<0.001
Grass competition	All	–	–	>0.05
Land condition	All	–	–	>0.05

^ACategorical variable; slope is the contrast between the nil and high classes.

stylo are tolerant of grazing, tolerant of frost, strongly perennial, indeterminant in flowering time, produce high

yields of seed with a significant portion that is hard-seed, recruit strongly and can achieve high plant densities, produce high biomass yields during suitable growing conditions, are capable of re-establishing from hard-seed after extended drought, and are widely adapted to the soils in the region (Cook *et al.* 2020).

Cultivars released in Australia for both *D. virgatus* and Caatinga stylo are strongly perennial with individual plants capable of surviving >5 years (Edye *et al.* 1998; Pengelly and Lloyd 2001); however, *D. virgatus* plants tend to survive for longer into extended drought periods than Caatinga stylo based on observations of grazier paddocks. Both species have indeterminate flowering periods once established and are capable of producing large amounts of seed during favourable growing conditions (>1000 kg seed ha⁻¹ per year in seed crops) (Edye *et al.* 1998; Cook *et al.* 2020). *D. virgatus* produces high levels of hard seed (>90% when harvested) with multi-year breakdown rates (Hopkinson and English 2004; S. Boschma, L. Bell, M. A. Brennan, S. Harden, unpubl. data), whereas Caatinga stylo tends to have lower levels of hard seed with large variation (<10–>80%) and faster breakdown rate (Jansen and Edye 1996; Anand *et al.* 2011; S. Boschma, L. Bell, M. A. Brennan, S. Harden, unpubl. data). Research trials record high seedling densities emerging after rain during summer for both species (Edye *et al.* 1998; Pengelly and Lloyd 2001). Both

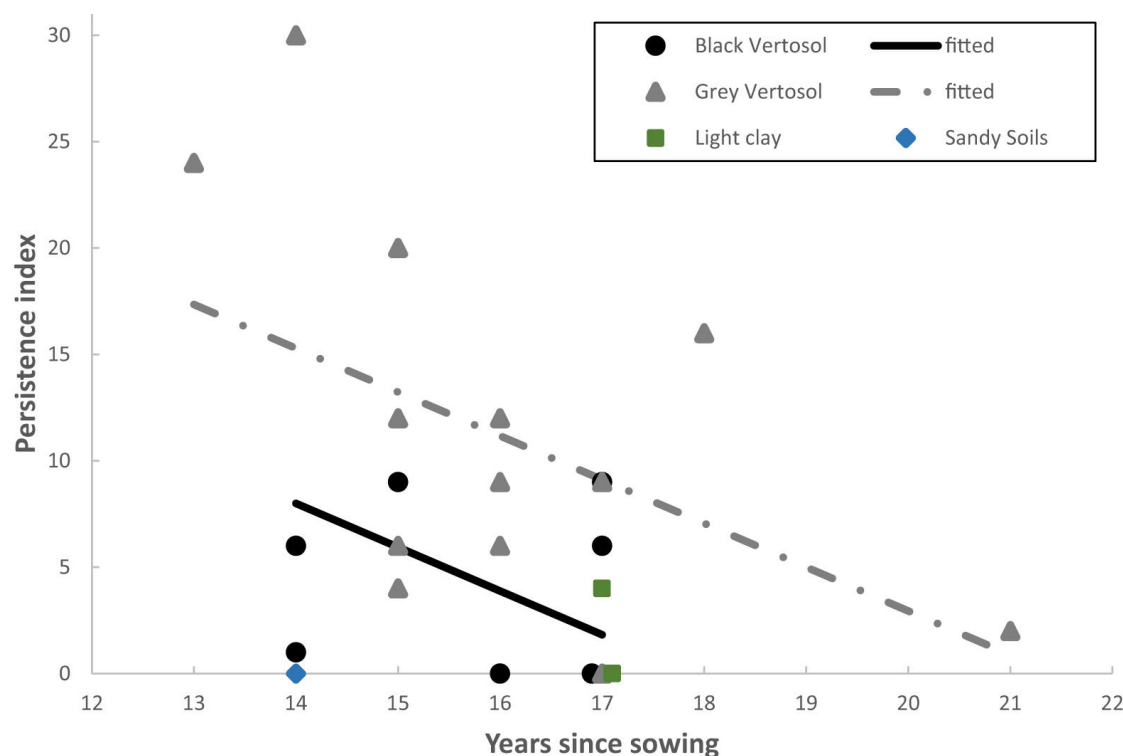


Fig. 3. Persistence of *Desmanthus leptophyllus* compared to years post sowing and soil type across the 26 sites where it was sown ($F_{4,21} = 3.92$, $P = 0.016$, $R^2 = 31.8\%$, slopes $P = 0.018$, soil types $P = 0.052$, the linear model includes separate soil type intersects).

species are frost tolerant (i.e. frost causes defoliation but plants survive and regrow from their base in spring) and can survive minimum temperatures of -5°C (Edye et al. 1998; Cook et al. 2020; Peck et al. 2022a). The combined traits of strongly perennial plants with frost tolerance, high seed production, hard-seededness, and high seedling densities make these two species widely persistent in the Brigalow Belt agro-climatic class (E4), which is characterised by variable rainfall with a summer dominant pattern, but on average, has moisture deficits in every month of the year with high interannual variation. It is also adapted and persistent in other locations with a similar climate (Hutchinson et al. 1992).

Caatinga stylo and *D. virgatus* are both persistent on clay soils (36 sites); however, Caatinga stylo is adapted to a wider range of soils as it also persisted on sandy soils. Both species can persist on soils with low plant available phosphorus (Peck et al. 2017a). The soil adaptation traits result in these species being widely adapted to the soils of the moderate rainfall sub-tropics of eastern Australia.

Caatinga stylo and *D. virgatus* are well adapted to moderate to high grazing pressure with low growing points and variable growth habit that adapts under grazing. Both species can also grow in a more erect growth pattern and produce high biomass yields during suitable growing conditions. These plant traits contribute to Caatinga stylo

and *D. virgatus* being well adapted to the grazing management that is typical of the research sites (33 sites were rated as moderate or high grazing pressure on the legumes) and commercial properties in the region.

Species with moderate or restricted persistence

D. leptophyllus was moderately persistent across the trial sites where sown. Leucaena, butterfly pea, and shrubby stylo persisted at a restricted range of soil and climate locations.

Desmanthus leptophyllus

D. leptophyllus showed moderate persistence overall but persisted at fewer than half of the sites where sown, with moderate persistence at a third of sites. Plants were generally larger than those of Caatinga stylo or *D. virgatus* and appeared to retain leaf later into autumn, however *D. leptophyllus* did not maintain a high plant density (plant m^{-2}) at a large percentage of sites. Persistence increased with summer rainfall and declined with years since sowing, which is consistent with previous observations that the species often performs well in the early years after sowing but populations decline over time (Pengelly and Conway 2000). There was a weak correlation between persistence and soil type (P value = 0.09), with *D. leptophyllus* having 'not persistent' ratings for sandy soils and light clays, low

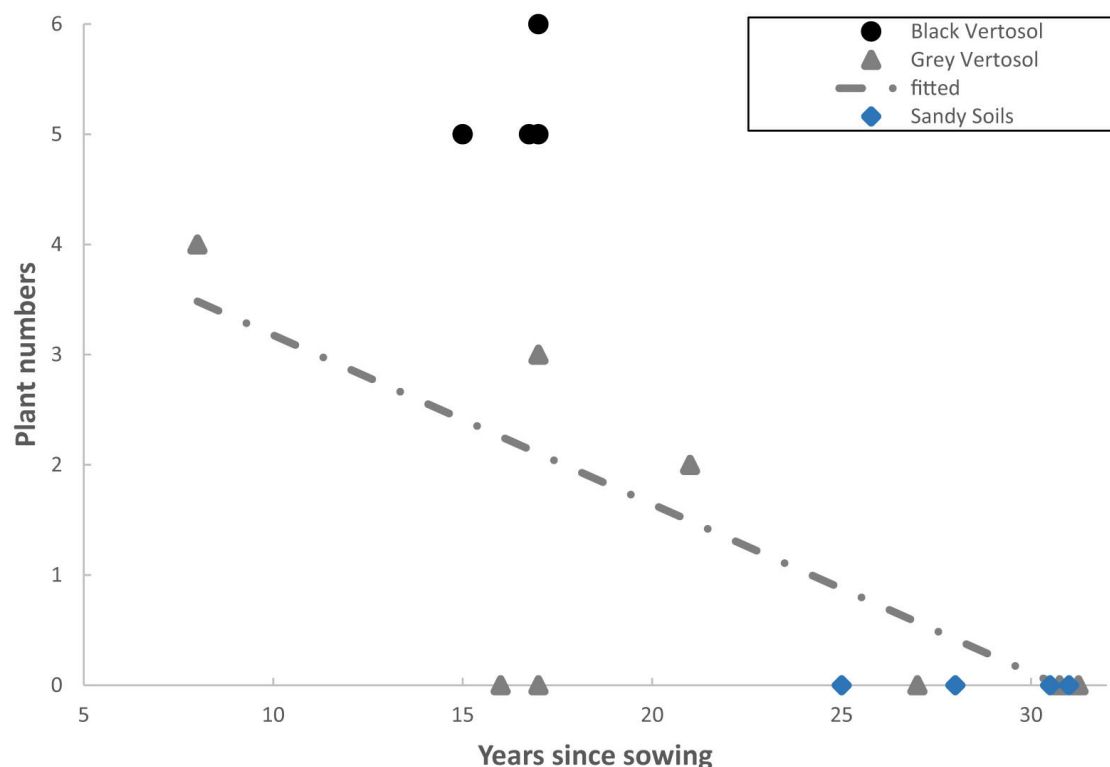


Fig. 4. Plant density rating of *Leucaena Leucocephala* compared to years after sowing on three soil types. ($F_{3,13} = 14.7$, $P < 0.001$, $R^2 = 72.0\%$, slopes $P = 0.018$, soil types $P < 0.001$, the linear model includes separate soil type intersects).

persistence ratings on Black Vertosols and moderate persistence on Grey Vertosols (Table 7).

Generally, *D. leptophyllus* flowers predominantly during autumn on declining day lengths, with existing commercial varieties (cvs. Bayamo, JCU1, JCU7) flowering during periods when moisture availability and temperature limit growth in most years in the sub-tropics (Cook *et al.* 2020). The most widely sown accession was cv. Bayamo, which is a medium-sized, mid-season flowering time and high yielding accession. Performance of other *D. leptophyllus* accessions was generally similar to Bayamo at sites where a wide range of *D. leptophyllus* accessions were sown; however, observations at a few sites suggest other accessions may have useful traits for the sub-tropics (e.g. earlier flowering). The correlation between persistence and summer growing season rainfall suggests that accessions with better adaptation to low rainfall combined with earlier flowering and high seed production would be useful for improving persistence; especially for more southerly latitudes where frosts are more prevalent, there is a lower percentage of annual rainfall during summer, and shorter daylengths during autumn and winter.

An earlier flowering variety with higher seed production than the existing commercial varieties of *D. leptophyllus* would be needed to improve persistence in the

Brigalow Belt climate zone, especially for more southerly latitudes. New varieties that maintain higher plant density combined with more appropriate agronomic practices for establishment and grazing management (such as spelling during peak flowering and seeding period) could lead to this species being more widely persistent in the sub-tropics as well as extending its range in the tropics.

Other large statured species of desmanthus such as *Desmanthus bicornutus* and *Desmanthus pernambucanus* were not recorded separately at the trial sites because they were sown at fewer sites and there were difficulties in identification to the species level under field conditions. Where other *Desmanthus* spp. were able to be identified, they generally had lower plant density than *D. leptophyllus*.

Leucaena

Leucaena was persistent at a third of sites where sown in this study despite being described as being broadly persistent in this region by other studies (Dalzell *et al.* 2006; Shelton and Dalzell 2007). *Leucaena* persisted on clay soils in the northern Brigalow (E4-N) and south-eastern Queensland (E7) agro-climatic class; but had poorer persistence in the colder agro-climatic classes (i.e. E4-S and E3) that experience more frost and rainfall during winter. *Leucaena* persistence ratings declined with time since sowing

especially on Grey Vertosol soils >15 years after sowing and in frostier southerly locations. These results align with a survey of graziers which reported that >75% of ageing leucaena pastures growing on non-alluvial clay soils had declined in productivity, with graziers noticing a decline in vigour approximately 15 years post sowing (Radrizzani *et al.* 2007).

Sowing leucaena on appropriate soils in suitable climate zones is essential for persistence, and therefore long-term productivity. Other research and commercial experience confirm that frost, soil fertility, and grazing management can all affect long-term persistence of leucaena (Dalzell *et al.* 2006; Radrizzani *et al.* 2007; Shelton and Dalzell 2007). Further research and extension is required to improve management for long-term persistence and productivity of leucaena, especially on grey Vertosol soils and in more southerly climates.

Butterfly pea

Butterfly pea persisted on Black Vertosol soils in the northern Brigalow Belt (E4-N) but did not persist on other soil types or in the southern Brigalow Belt (E4-S). The results suggest that butterfly pea should only be recommended for short term pastures (<5 year pasture phase) on Grey Vertosol, light clay, and sandy soil types in the northern Brigalow Belt (agro-climatic class E4-N) and is not recommended in southern Queensland (agro-climatic classes E4-S, E7, and E3). The results from this study support previous recommendations (Collins and Grundy 2005).

Shrubby stylo

Shrubby stylo persistence was strongly related to soil type, with high persistence on sandy soils and poor persistence on clay soils. Cultivars Seca and Siran are widely established on light textured soils in areas with low frost incidence in central and north Queensland, but have performed poorly in southern inland Queensland, attributed to poor frost tolerance (Bell *et al.* 2016). Several non-commercial accessions showed persistence at frosty southern sites, suggesting potential for selecting or breeding improved cultivars for these colder environments that could extend the geographic range that is suitable for stylo-based pastures into southern Queensland and northern New South Wales (Peck *et al.* 2022a).

Species with poor persistence

Several species that historically were commonly recommended for pastures in the sub-tropics showed little long-term persistence under climate and soil types represented in this study. Atro, burgundy bean, lucerne, Caribbean stylo, and round-leaf cassia persisted at very few sites or not at all. Lotononis and fine-stem stylo persisted at only two sites but were sown at less sites.

Macroptilium spp.

Atro (*M. atropurpureum*) and burgundy bean (*M. bracteatum*) persisted at one ungrazed trial site and one site with low grazing pressure (i.e. only grazed when crop stubble in the surrounding paddock was grazed). Both burgundy bean and atro have been widely recommended and sown in pastures in Queensland. Burgundy bean was released as a ley legume (Cook *et al.* 2020), but has been marketed as a persistent legume (Barenbrug 2025). Atro was one of the earliest released pasture legumes for northern Australia, was widely marketed and sold for several decades, and is still being recommended by some farm advisors (Jones 2014). The results from this study are consistent with previous research and commercial experience that demonstrate poor persistence when combined with grass under grazing in the Brigalow Belt bioregion (Peck *et al.* 2011; Jones 2014; Bell *et al.* 2016). Both legume species can perform strongly in the first 2–5 years after sowing and are also prevalent in ungrazed situations (e.g. roadsides). These legumes should not be recommended for long-term pastures based on these results.

Lucerne

No lucerne plants were found at any site, which suggests there was no recruitment of seedlings. Lucerne can be useful in short to medium term pastures (5–10 years) and hay crops in southern Queensland and is more widely used in New South Wales but does not persist long-term (Lloyd *et al.* 2007).

Caribbean stylo

Caribbean stylo did not persist at any site. This is likely owing to all sites in central Queensland being on clay soils, and southern Queensland sites being subject to regular frosts (Cook *et al.* 2020). Commercial varieties of Caribbean stylo are not tolerant of frost. Caribbean stylo has been widely used commercially, and has persisted on light textured soils in central and north Queensland (Lambert and Graham 1996; Partridge *et al.* 1996).

Round-leaf cassia

Round-leaf cassia did not persist at any sites, which contrasts with results in other climate and soil locations. Round-leaf cassia has persisted to the point of dominating pastures on particular soils in more easterly districts (i.e. agro-climatic class E7) and monsoonal northern districts (i.e. north Queensland, parts of the Northern Territory) (Bell *et al.* 2016). Round-leaf cassia has not persisted at the assessed sites in the Brigalow Belt south agro-climatic class and the authors are unaware of examples where it has persisted in commercial pastures unless protected from frost (e.g. under trees, tops of hills). In the Brigalow Belt north agro-climatic class, round-leaf cassia does persist on sandy soils (Bell *et al.* 2016).

Lotononis

Lotononis was sown at six sites and persisted at two of the more easterly, higher rainfall trial sites on sandy soils. Lotononis has previously demonstrated persistence for >10 years in commercial pastures in more coastal districts (Bell *et al.* 2016). Lotononis should not be recommended for the Brigalow Belt; however, it could have a role in higher rainfall districts. Commercial use of lotononis is constrained by having a very small and difficult to handle seed (Bell *et al.* 2016). Commercial seed has not been available for more than a decade, indicating little or no ongoing use.

Fine-stem stylo

Fine-stem stylo persisted on two sandy soil trial sites located in eastern, higher rainfall trial sites of the Brigalow Belt south agro-climatic class (E4-S) but did not persist at five other sites in this study. Fine-stem stylo has not persisted at nine recently sown trial sites in the E4-S agro-climatic class (Peck *et al.* 2022a, 2022b). Fine-stem stylo is considered to be persistent on free draining soils in the higher rainfall E7 agro-climatic class of south-eastern Queensland (Partridge *et al.* 1996; Bell *et al.* 2016). The results from this study support previous research results and industry experience, which recommends fine-stem stylo only for sandy soils with higher rainfall than what is experienced in most of the Brigalow Belt bioregion (Partridge *et al.* 1996; Bell *et al.* 2016).

Comparison with grazer experience

The results of this study broadly support grazer perceptions that many pasture legumes historically recommended for the Brigalow Belt have limited long-term persistence. However, the widespread persistence of Caatinga stylo and *D. virgatus* contrasts with some grazer and seed industry concerns about their long-term persistence and reliability (Peck *et al.* 2010; Buck and Lawrence 2011). Graziers reported that only the 'short variety' of desmanthus was persisting (i.e. *D. virgatus* cv. Marc), but the 'tall varieties' had died out (i.e. cvs Uman and Bayamo) (Peck *et al.* 2010), which aligns with the results herein.

Some of the differences between grazer experience of Caatinga stylo and *D. virgatus* and trial observations likely reflects variable establishment success. Previous work has identified poor establishment as a major constraint to successfully incorporating legumes into competitive buffel grass pastures in commercial paddocks in the moderate rainfall sub-tropics (Peck *et al.* 2017b). Where establishment is successful, these results indicate that Caatinga stylo and *D. virgatus* can persist across a wide range of environments and grazing pressures. More widespread adoption of better

agronomic practices by graziers would improve the reliability of establishing these persistent legume species into existing grass pastures to achieve long-term productivity gains (Peck *et al.* 2022b).

Graziers generally described leucaena as being widely persistent (Peck *et al.* 2010), especially in central Queensland; however, it did not persist at the majority of sites in this study. Graziers routinely use agronomic practices to reliably establish leucaena in the sub-tropics (e.g. fallow for >6 months to store soil moisture and control weeds, use selective post emergent herbicides, sow with precision planters), but generally do not use these practices to establish other pasture legumes (Dalzell *et al.* 2006; Peck *et al.* 2022b). Grazer perceptions that leucaena is more persistent than Caatinga stylo and *D. virgatus* are likely owing to more reliable establishment.

Long-term persistence of the other legume species largely aligns with graziers' experience of commercially available legume varieties, however some non-commercial accessions have had better persistence at some sites.

Implications for pasture development and research

The results reinforce the importance of selecting legumes with demonstrated long-term persistence and matching species to appropriate soil and climatic conditions. In general, early pasture research failed to adequately measure and consider long-term persistence of legume populations over the long-term, especially during extended multi-year droughts where adult plants die and potentially all emerging seedlings die due to isolated falls of rain, which reduces or exhausts the seedbank in the soil (Jones 2014). A strength of this study is that long-term trials have exposed pasture legumes to a greater range of seasonal variability, including multi-year droughts; and a network of sites exposes the plants to a range of management factors (e.g. grazing management, range of soil types and seasonal conditions). Implications for future research are to consider duration, management or treatment imposed, measurements or observations taken, range of sites required to represent climate and soil variation, and the need for an ecological approach that adequately considers plant population dynamics over the long-term when designing pasture evaluation programs.

In the Brigalow Belt north zone, several legumes appear suitable for long-term pastures depending on soil type, including Caatinga stylo, desmanthus species, shrubby stylo, and leucaena on appropriate soils. In the more frost prone Brigalow Belt south zone, the range of reliable summer growing legumes is narrower, particularly on low-fertility sandy soils.

D. leptophyllus and *leucaena* can produce high yields in the short term but may be better suited to medium-term pastures (10–15 year pasture phases) that are periodically re-sown. Economic analyses suggest that such systems may be profitable despite establishment costs (Thompson et al. 2026), although grazer reluctance to re-establish pastures remains a constraint.

The study covered a wide geographic area with 44 sites evaluated; however, some soil–climate combinations were under-represented, particularly sandy soils and more southerly environments. There were no sites assessed in New South Wales and the sites in the far south of Queensland did not have current varieties of *desmanthus* and *Caatinga stylo* sown due to research in these regions historically focusing more on temperate legumes. Additional long-term trial sites are required to cover important soil-climate combinations, especially in southerly latitudes and frosty locations.

Variation among original trial designs also limited the consistency of long-term observations. Large plots (50–200 m²) were good for commercial varieties and short-listed accessions with larger amounts of seed available for sowing. Plots of this size were generally able to cope with disturbance by grazing, and the plot locations were able to be identified for >20 years post sowing. By contrast, trials sown in small plots generally resulted in small patches of legumes where it was difficult or impossible to determine which accessions were persisting. Future pasture evaluation trials would benefit from permanent geo-referencing, consistent plot identification, and improved long-term data archiving to support re-evaluation of legacy experiments. This is particularly important as future access to late-career and retired pasture agronomists cannot be relied upon.

Conclusion

This study provides a more long-term and directly measured assessment of persistence of pasture legumes across the Brigalow Belt bioregion in the moderate rainfall sub-tropics of eastern Australia, which could provide useful insights for other regions of the world. Direct assessment of plant populations many years after establishment (average of 17.5 years after sowing in this study) provided a robust and directly measured assessment of persistence compared to shorter-term (3–10 year) studies that are commonly used to evaluate environmental adaptation of pasture legumes that measure indicators of persistence under a relatively limited range of seasonal variation.

The results from this study support grazer observations that many commercially released legumes that are recommended for the moderate rainfall sub-tropics have limited long-term persistence. Of the 13 species assessed, only two were widely persistent across trial sites, while four showed persistence within a narrower range of soil type

and climate zones. Seven commercially released legumes demonstrated very little or no persistence.

Caatinga stylo (*S. seabrana*) and *D. virgatus* demonstrated consistent long-term persistence across a wide geographic range, indicating strong potential to improve pasture productivity across large areas of the moderate rainfall sub-tropics of eastern Australia and similar subtropical to tropical environments. *D. leptophyllus* showed moderate persistence, and observations suggest that selection of improved accessions may enhance its long-term performance.

Leucaena (*L. leucocephala*) and shrubby stylo (*S. scabra*) were persistent when sown in suitable climate zones and soils and managed appropriately. Butterfly pea (*C. ternatea*) persisted only on Black Vertosol soils in central Queensland; however, on other soils in central Queensland, it is suited to short-term pastures but is not suited to southern Queensland climate zones. In contrast, *atro* (*M. atropurpureum*), burgundy bean (*M. bracteatum*), and lucerne (*M. sativa*) showed poor persistence at all sites and are not suited to long-term grazed pastures in the sub-tropics. Caribbean stylo (*S. hamata*), round-leaf cassia (*C. rotundifolia*), fine-stem stylo (*S. guianensis* var. *intermedia*), and lotononis (*L. bainesii*) showed only limited adaptation within the region.

Overall, the study demonstrates that cultivars of relatively few of the legume species tested provide reliable long-term persistence in the moderate rainfall sub-tropics of eastern Australia. Successful pasture development therefore depends on selecting species that can be persistent in the long-term and matching these legume species to soil type and climate.

Research and extension effort should focus on improving successful industry adoption of legume species that have been shown to be persistent in the long-term, through improved agronomic and grazing practices to improve establishment reliability and long-term productivity. Other research opportunities include identifying germplasm with useful traits to fill gaps in environmental adaptation (e.g. adaptation to frosty sandy soils, early flowering to avoid frost) or production traits (e.g. better leaf retention), and improved management practices to improve long-term persistence and productivity of promising species (e.g. grazing practices to promote seed production and recruitment of *D. leptophyllus*).

Supplementary material

Supplementary material can be accessed from the article page online.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. This research was funded by the Queensland Government through the Department of Primary Industries and Meat and Livestock Australia as part of the 'Improving productivity of rundown sown grass pastures' project (B.NBP.0639).

Acknowledgements. The trial sites were established over decades by pasture agronomists from the Queensland Department of Primary Industries and the Commonwealth Scientific and Industrial Research Organisation. Most of the old trial sites described in this paper are hosted on private properties. The completion of this study would not have been possible without the contributions from many graziers whose support is gratefully acknowledged. Stuart Buck provided technical assistance in collecting data from some sites. Louise Walker provided technical assistance in entering and interpreting data. David Mayer conducted the statistical analysis.

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