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Sown grass–legume production paddocks have potential to improve beef enterprise productivity in the seasonally dry monsoonal tropics of northern Queensland

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ABSTRACT

The production of tropical cattle breeds for feeder or live export markets is the dominant primary industry in the seasonally-dry monsoonal tropics of northern Queensland. Natural woodlands and grasslands are key feed resources, with smaller cleared areas used for pasture development. Extended dry season feed deficits plus land condition decline limit animal growth and market options for producers. Previous research in northern Queensland using introduced legumes sown into native grass pastures demonstrated that intensively-managed 'production paddocks' using well-adapted and productive grasses and legumes could improve weaner and steer nutrition during the early to mid-dry season, enabling earlier sale or higher sale weights of cattle. Promising introduced grasses and legumes were tested at two sites of contrasting fertility in northern Queensland to test suitability for production paddocks. Replicated small-plot combinations of sown grass and legume on fertile and infertile soils resulted in pasture yields up to three times greater than those typically achieved on native pastures. A range of grasses (*Bothriochloa, Brachiaria, Digitaria, Panicum, Urochloa*) formed dense swards when soil-available phosphorous and sulfur were supplemented with fertiliser. Competitive legumes (*Stylosanthes scabra* and *S. seabrana* (on both fertile and infertile soils) and *Clitoria ternatea* (fertile soil)) increased total herbage yields (up to 14 t DM/ha) when grown with these grasses. The legume component contributed leaf with high feed value (15–20% crude protein and 8–10 MJ/kg metabolisable energy) during the wet and dry seasons, which should enable producers to reduce dietary herd inefficiencies. The most competitive grasses and legumes also suppressed plants (*Bothriochloa pertusa, Themeda quadrivalvis, Chamaecrista rotundifolia*) of low feed value for cattle, which otherwise dominated the sites. Preliminary economic analyses using the experimental results showed the development of 'production paddocks' to be profitable on fertile and infertile land types.

Keywords: beef production, legume pastures, monsoonal dry-tropics, northern Australia, stylos, tropical pastures, weed suppression.

Introduction

Beef cattle production is the principal land use in the seasonally-dry monsoonal tropics of northern Australia, which includes a 600–1000 mm average annual rainfall zone in northern Queensland (Fig. 1). This latter region contains ~30% of the total Queensland cattle herd, which in turn approximates 45% of the June 2024 national Australian herd of ~30.4 million head (Meat and Livestock Australia 2025). Weaners and steers of tropical cattle breeds for feeder (store) and live export markets mostly to Southeast Asian countries are the key agricultural products of the region. Key profit determinants are breeding heifer and cow productivity (weaning and death rates) and sale weights of weaners and steers (McLean *et al.* 2014). Native grass pastures in woodlands and natural treeless plains are the key feedbase in the seasonally-dry tropics, with

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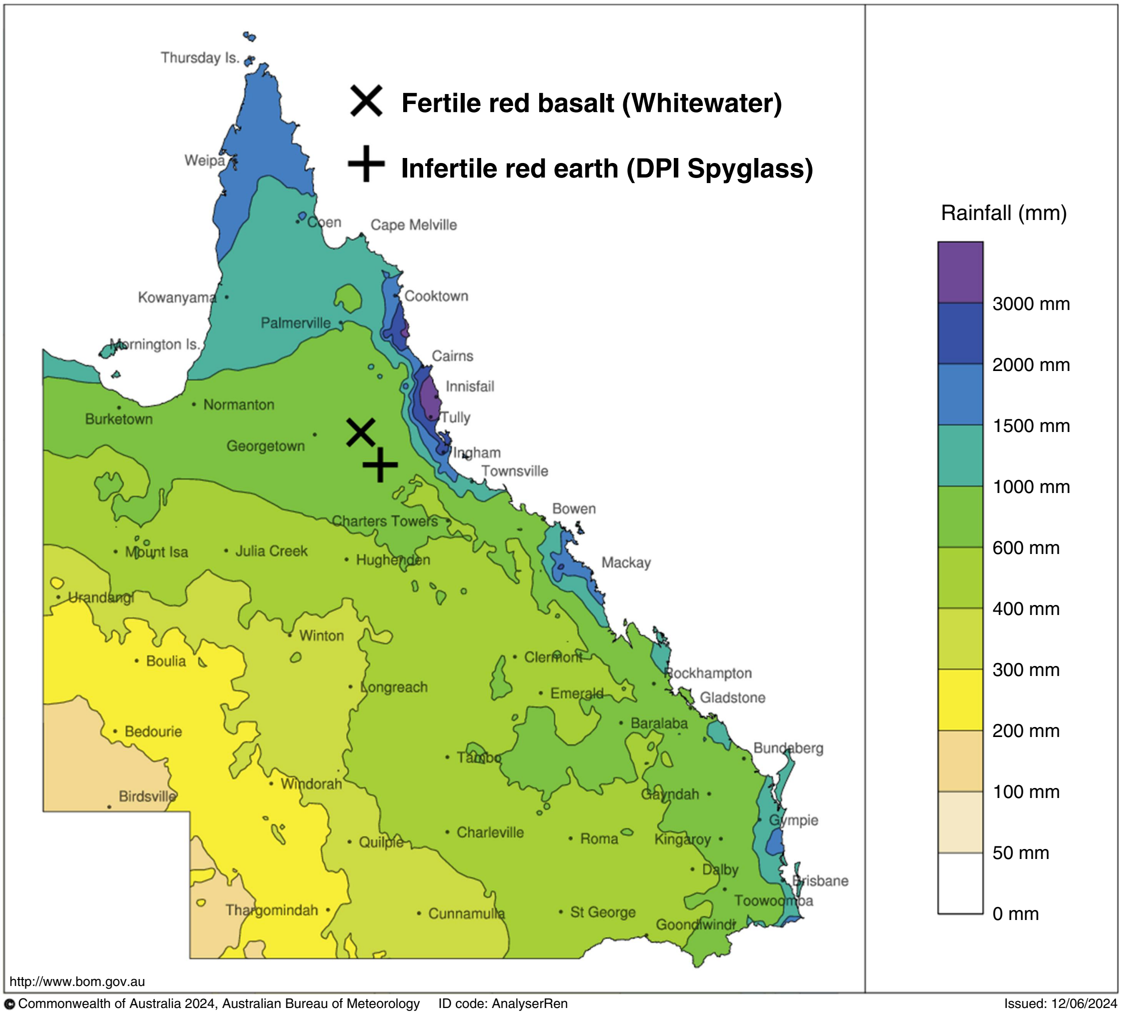

Fig. 1. Locations of the two experiment sites in Queensland, Australia. Isohyets represent mean annual average rainfall (1991–2020) (Australian Bureau of Meteorology).

forage type being dependent on geological soil development processes and rainfall. Most (geologically older) soils are considered infertile, with low levels of plant-available phosphorous and sulfur, but younger soils (basalt and alluvial) are considered more fertile.

Management of the dry-season 'feed gap' when forage yield is inherently low is one of the greatest challenges to beef producers in northern Queensland, requiring careful management to maintain pasture condition (Rolfe *et al.* 2016). Native pasture growth is seasonal owing to a 3–4 month monsoonal summer growing period (December–March), followed by an extended dry season (McCown 1981). This results in feed volume and quality (digestible energy and protein) deficits when good nutrition is required by livestock. In the study region, this includes growing animals for sale (weaners and steers) and reproductive females for weaner production (heifers and cows). High-protein supplements such as molasses fortified with urea can improve animal nutrition in the dry season (Winks *et al.* 1982), but are often expensive, and still result only in extended growth paths (McLennan 2014). An additional challenge is long-term decline in useful perennial grasses and increases in herbaceous and woody weeds, which limits animal growth rates and the number of cattle that can be supported on individual properties (Ash *et al.* 1995; Shaw *et al.* 2025). In northern Queensland, this has been exacerbated by widespread naturalisation of early flowering and low-biomass introduced grasses such as Indian couch (*Bothriochloa pertusa*), which have limitations as cattle feed (Spiegel 2023). Sown grasses and legumes that extend the period of forage supply into the dry season could be used to address this shortfall in forage supply.

A historical strategy to increase pasture productivity was to either sow introduced grasses considered to have desirable production characteristics (e.g. *Cenchrus ciliaris, Urochloa mosambicensis*) in small areas on soils with the best available fertility with or without legumes, or to integrate introduced hardy legumes (*Chamaecrista rotundifolia, Desmanthus spp., Stylosanthes* spp.) into native pastures by broadcasting during the wet season over a larger scale (Walker and Weston 1990; Cox *et al.* 2016). In the 1990s, the incorporation of *Stylosanthes* spp. into native grass pastures on low-fertility soils was shown to increase stocking rates and improve weaner and steer growth in the seasonally dry monsoonal tropics of northern Queensland (Anon 1994*a*, 1994*b*). Further increases in stocking rate and animal growth were achieved by applying fertiliser phosphorus and sulfur. A retrospective bioeconomic analysis of adopting this legume + fertiliser system on 500 ha of a 30,000 ha (typical size) property and modelling stock flows, costs and sales over 30 years found these production paddocks to be highly profitable, with low peak deficits and payback periods of 9–12 years compared to undeveloped grasslands, depending on the assumptions being used (Bowen *et al.* 2019). Development of this 'production paddock' concept stalled during the 1990s and 2000s, owing to a lack of continued investment in sown-pasture research and extension. However, in 2014, the Queensland Government, collaborating with the Australian beef industry, began to assess new and historical grass and legume cultivars and promising but unreleased lines under management suitable for production paddocks (Cox *et al.* 2019).

The results reported below relate to the second phase of research (2019–2023), after identification of productive and persistent grasses and legumes from single-taxon replicated plot experiments on a range of land types (Cox *et al.* 2022). The principal objective of this study was to assess how combinations of promising sown grasses and legumes with a range of growth habits perform under grazing on high- or low-fertility soils when managed as a 'production paddock' within land types typical of moderate land condition in the seasonally-dry monsoonal tropics in northern Queensland. The successful results from the study were used to progress the concept of 'legume production paddocks' at paddock scales on commercial beef properties within this zone.

Materials and methods

Two experimental sites were established on key beef production land types, including a fertile red basalt soil on a commercial cattle breeding property ('Whitewater' station), and an infertile red earth soil on a government cattle research property (Queensland Government Department of Primary Industries 'Spyglass' station) (Fig. 1, Table 1). The sites represent two distinct woodland vegetation communities used for beef production (Queensland Government 2024*a*, 2024*b*). The sites were located in the northern Queensland seasonally-dry monsoonal tropics, approximately 200 km

Table 1. Characteristics and management of sites used to test production paddocks in northern Queensland.

Site feature/management Property name	Fertile site 'Whitewater'	Infertile site 'DPI Spyglass'
Location (°S/°E)	Mount Surprise (18.14/144.64)	Charters Towers (19.49/145.69)
Mean annual rainfall (median)[A]	791 (806)	556 (509)
Soil type	red basalt (kraznozem)	red earth (free-draining red clay)
pH_{water}; $P_{Colwell}$; PBI; S_{MCP}	6.6; 240; 220; 5	6.2; <5; 19; 7
Dominant vegetation (fewer)[B]	BP, TQ, HC (SH, SS) (uncleared)	BP, CC, CR, (SH, SS), UM (cleared)
Fenced site dimensions (ha)	6	4
Grass and legume treatments	7 grasses (1 failed) × 8 legumes	7 grasses × 9 legumes
Plots: area (m^2), (m width × m length) replications, total number	54 (6 × 9), 3, 192	144 (8 × 18), 3, 189
Site preparation methods	No fallow period; cultivation × 2; glyphosate × 1; roll	One year fallow; cultivation × 2; glyphosate, roll
Pre-plant fertiliser (kg/ha)	120 ammonium sulfate	120 single superphosphate
Sowing date	27 Feb 2019	5 Feb 2020
Sowing methods	Broadcast and roll	Broadcast and roll
Sowing rates (in parentheses) (kg/ha) and target viability	Grasses: (3): *Brachiaria/Panicum/Urochloa* 80%, *Digitaria* 70%, *Bothriochloa* 50% Legumes: *Clitoria* (8), 80%, *Macroptilium* (6), 80% *Desmanthus/Stylosanthes* (3), 60%	
Rainfall after sowing (mm)	28 first 4 weeks + 20 (6 months)	201 first 4 weeks + 173 (6 months)

[A]Bureau of Meteorology (BoM) records: Mount Surprise (BoM station 30036) 1873–2022; Charters Towers (30137) 1993–2018.
[B]BP, *Bothriochloa pertusa*; CR, *Chamaecrista rotundifolia*; CC, *Cenchrus ciliaris*; HC, *Heteropogon contortus*; SH, *Stylosanthes hamata*; SS, *Stylosanthes scabra*; TQ, *Themeda quadrivalvis*; and UM, *Urochloa mosambicensis*.

from the coast and inland of a subcoastal range. The infertile site was a previously cleared and degraded sown pasture dominated by *Chamaecrista rotundifolia*, an early flowering pasture legume of moderate feed value. The fertile site was within a large paddock of uncleared woodland grazed by cows and calves, dominated by *Bothriochloa pertusa* and *Themeda quadrivavlis*, grasses with short growing seasons owing to early maturation. The land type of both sites support *Heteropogon contortus* pastures in the pristine state (Tothill and Gillies 1992). Over 80% of the rainfall is recorded over summer (December–March), and winters may include one or two light frosts that pause plant growth rather than kill plants.

In total, 7 grasses and 10 legumes were tested over the two sites as 1 grass × 1 legume combinations in replicated small plots (Table 2). The fertile site was sown 27 February 2019 and the infertile site on 5 February 2020. All grasses were sown at each site, whereas legume selections varied for each site on the basis of previous performance in small-plot monocultures. The fertile site included a 'no sown grass' treatment, following establishment failure of one grass species (only seed of low viability was commercially available). A complete factorial design of one grass and one legume in each plot was used for a total of 192 plots at the fertile site and 189 plots at the infertile site. The legumes were randomly allocated to the small plots within randomly allocated grass strips (complete block with three replicates), resulting in 6 × 9 m^2 (fertile site) or 8 × 18 m^2 (infertile site) plots for each grass × legume combination. The seedbeds were prepared for high seedling establishment by using crop establishment practices including cultivation and herbicide application to control previously established and emerging weeds. Fertiliser on the basis of prior soil tests was applied prior to final cultivation, as follows: 120 kg/ha ammonium sulfate at the fertile site (high soil-available phosphorous but low sulfur) and 120 kg/ha single superphosphate at the infertile site (low for both elements) (Table 1). Legume seeds were inoculated with commercially recommended strains of *Bradyrhizobium* inoculant and the grass and legume seeds sown by broadcasting onto a rolled seedbed, and rolling post-broadcasting. Sowing rates were based on Cook *et al.* (2020) and adjusted on the basis of seed tests (top of paper test, 35/20°C: 16/8 h). No irrigation (or any other intervention) was used.

Grass and legume establishment (population density) was measured in six randomly located 0.25 m^2 quadrats per plot. Low rainfall post-establishment at the fertile site (Table 1) required repeat seedling counts over the dry season (3 weeks) to trace population decline, whereas at the infertile site only one measure 6 weeks after sowing was required. Visual assessments of live grass, legume or other plant ground cover (0 = none present, 10 = complete cover) were conducted at the end of the first dry season and first growing season after establishment, using either two (fertile site with smaller plots) or five (infertile site with larger plots) visual assessments within randomly placed 0.5 m^2 quadrats per plot.

The plots were ungrazed in the first dry season, and wet season spelled thereafter. Wet season biomass was measured when weather forecasts indicated a poor prognosis for further rainfall before dry-season grazing. Heifers or steers were introduced in May–June and grazed the fenced area containing the plots. High stocking rates and short grazing times were used each year to approximate grazing under an intensively and rotationally grazed production paddock system, including 10–18 head (1.0–2.3 adult equivalents (AE)/ha) 3–6 weeks at the fertile basalt site and 12–28 head (3.9–6.4 AE/ha) for 10–15 days at the red earth site. The plots were grazed until it was estimated by experienced technicians by using a visual volumetric herbage yield estimation method that there was a residual yield of 1.0–1.5 t DM/ha. This was considered sufficient to maintain enough end-of-dry-season cover to reduce the risk of soil degradation and stress to the grazing animals. Visual assessments of grazing intensity (0 = not eaten, 5 = >90% grazed to ground level) completed on each plot within a week of introducing the cattle to the trial paddocks confirmed that all of the grasses and legumes tested were readily eaten.

In the 2020–2021 growing season, herbage yield was estimated at the end of the growing period by cutting two 0.25 m^2 quadrats per plot (360+/site), separating species while fresh, drying at 65°C until constant weight, and separating all legumes into leaf and stem components before weighing. Subsamples were ground and submitted to an accredited laboratory (Dairy One™) for feed-value analysis (digestible forms of nitrogen (protein) and energy, minerals) by using wet chemistry (in the absence of suitable near-infrared spectroscopy (NIRS) calibrations). In the 2022–2023 growing season, herbage yield was measured using a visual appraisal method of yield and composition calibrated using herbage cuts and regression analysis (after Tothill *et al.* 1992). This enabled assessment of all pasture components individually to assess the influence of the sown grasses and legumes on naturalised species. The R^2 values of the officer assessments against test samples (15) ranged 0.92–0.94 at the fertile site and 0.74–0.95 at the infertile site.

Measuring animal liveweights was not possible owing to the experimental scale and design. However, intermittent grazing based on estimation of available feed was adopted once the trials concluded in June 2024, typically grazing to a residual of ~1.2 t DM/ha before removing cattle (heifers at the fertile site and cow–calves at the infertile site). Legumes (*Stylosanthes seabrana* and *Clitoria ternatea*) had spread across the 6 ha site at the fertile site and it was decided to assess diet quality compared with the neighbouring unimproved paddock as a simple demonstration for beef producers. Fresh faecal samples were collected approximately every 6 weeks from six grazing weaner heifers introduced in September 2024 (and grazed until January 2025), with the same sampling procedure conducted by using cows

Table 2. Grasses and legumes grown as 1:1 combinations in replicated small plots at two sites in northern Queensland, Australia.

Botanical name	Identifier (Australia)	Common name	Characteristics	Fertile site	Infertile site
Grasses					
Bothriochloa insculpta	TGS125652B	Creeping bluegrass	Stoloniferous perennial, mid-season flowering	Y	Y
Brachiaria brizantha syn. *Urochloa brizantha*	Mekong	Brizantha	Tufted perennial, late flowering	Y	Y
Digitaria milanjiana	Jarra	Finger grass	Stolonferous/rhizomatous perennial, early flowering perei	Y	Y
Panicum coloratum	ATF714	Coloratum	Tufted perennial, early flowering	Y	Y
Panicum hybrid (*P. maximum* × *infestum*)	NuCal Massai	Panicum hybrid	Tufted perennial, late flowering	Y	Y
Panicum maximum syn. *Megathyrsus maximum*	Gatton	Panic	Tufted perennial, mid-season flowering	Y	Y
Urochloa mosambicensis	Manzini	Sabi	Stoloniferous perennial, early flowering	Y	Y
Legumes					
Clitoria ternatea	Milgarra	Butterfly pea	Twining perennial herb, early flowering	Y	Y
Desmanthus spp. (three species composite)	Progardes	Desmanthus	Perennial subshrub, mid-season flowering	Y	Y
Desmanthus leptophyllus	TQ90	Desmanthus	Perennial subshrub, mid-season flowering		Y
Desmanthus virgatus	Marc	Desmanthus	Perennial subshrub, mid-season flowering		Y
Macroptilium atropurpureum	TGS84989	Atro	Twining perennial herb, late flowering	Y	Y
Macroptilium gracile	TGS849	Gracile	Short-lived (annual) early flowering twining herb	Y	Y
Stylosanthes hamata	Amiga	Caribbean stylo	Short-lived (annual) early flowering subshrub	Y	Y
Stylosanthes guianensis	Nina (ATF3308)	Common stylo	Perennial subshrub, late flowering	Y	
Stylosanthes scabra	Seca	Shrubby stylo	Perennial subshrub, mid-season flowering	Y	Y
Stylosanthes seabrana	Unica	Caatinga stylo	Perennial subshrub, mid-season flowering	Y	Y

concurrently grazing the adjacent paddock. The samples were assessed to estimate dietary feed value (crude protein, metabolisable energy) and broad composition (grass or non-grass) by using NIRS (Dixon and Coates 2010). Rainfall was measured on site, and temperature records were obtained from nearby Bureau of Meteorology stations (https://www.bom.gov.au/climate/data/?ref=ftr).

The sown grass and legume populations at each site and sampling time were analysed separately by ANOVA in Genstat for windows 19th edition (VSN International, http://genstat.co.uk/). Total pasture yield, total grass yield, total legume yield, percentage legume leaf, crude protein, and metabolisable energy were also analysed by ANOVA. In all ANOVAs, a factorial treatment structure, including the main effects and interaction of grass and legume species, was fitted. However, because the primary interest was comparing the performance of the tested grasses or legumes at the species level, the focus was on the main effects. A split-plot structure was fitted as the random terms to represent the experimental design. All significance testing was performed at the 0.05 level and where a significant effect was found, the 95% least significant difference (LSD) was used to make pairwise comparisons. Square-root transformations were required for the analyses of grass and legume populations at the fertile site and legume populations only at the infertile site to satisfy the homogeneity of variance assumption. For ease of interpretation, the back-transformed means are presented in this paper. An exponential regression model was fitted to determine the effect of sown grass and legume biomass on the biomass of the three naturalised dominant species.

Results

Plant establishment

Rainfall for establishment was marginal at the fertile site, with only 28 mm of recorded rainfall in the first 4 weeks post-sowing, compared with 201 mm at the infertile site sown the following year (Table 1). Rainfall during the dry season following sowing was also low at the fertile site. Despite this, initial establishment of sown grasses and legumes was highly successful at both sites (Tables 3, 4). In general, larger-seeded grasses and legumes had the lowest populations, and the establishment of the *Desmanthus* lines was also low at the infertile site. Initial populations were considered satisfactory for experimentation and populations were sustained at the infertile site by the high rainfall. However, the low rainfall at the fertile site reduced the number of surviving grass and legume seedings over the dry season. The legumes survived better than the grasses, mostly halving in population by October, whereas the grasses declined more than four-fold at the fertile site. The notable exceptions were as follows: (legumes) *Macroptilium gracile*, which behaves as an annual in this environment, with many plants producing seeds but then dying; (grasses) *Brachiaria brizantha*, where a higher proportion of seedlings survived than for the other grasses at the fertile site. Whereas most grasses and legumes failed to seed in the 12 months after establishment at the fertile site, all grasses and legumes seeded within 6 months of sowing at the infertile site (data not presented).

Plant growth and herbage yields

Grasses dominated at the infertile site in the first year after sowing, as evidenced by end of growing season measurements of green cover in the season after sowing, whereas the same measures showed that the legumes were more dominant at the fertile site (data not presented). Plant growth was rapid at both sites, and both were suitable for grazing by April in the year post-sowing. Grasses and legumes seeded by August in all years after establishment, and time of flowering was in accordance with the description in Table 2 (data not presented). All grasses and legumes were well-eaten during the dry-season grazing, with most leaves and smaller stems having been consumed by the time the animals were removed. Regrowth in the absence of rainfall was minimal following dry-season grazing, but was rapid for all the grasses and legumes after storm and monsoon

Table 3. Mean initial establishment (plants/m^2) of sown grasses measured during the first dry season after establishment.

Item	*Bothriochloa insculpta*	*Brachiaria brizantha*	*Digitaria milanjiana*	*Panicum coloration*	*Panicum* hybrid	*Panicum maximum*	*Urochloa mosambicensis*	No sown grass
Fertile red basalt site (sown 27 February 2019)								
23 April[A]	54.1c	22.0b	19.9b	61.1c	63.4c	29.2b	113.4d	0.6a
23 July[A]	16.7c	15.7c	2.1ab	13.3c	12.6c	6.6bc	65.1c	0.1a
23 October[A]	12.5c	10.9c	0.3a	3.4b	3.9b	4.6b	31.5d	0.0a
Infertile red earth site (sown 5 February 2020)								
17 March	32.4a	25.9a	35.9a	23.9a	58.1b	22.4a	36.7a	–

Means represent data pooled across legumes. Means with the same letter within a row are not considered different at the 5% probability level.
[A]Back-transformed data.

Table 4. Mean initial establishment (plants/m^2) of sown legumes measured during the first dry season after establishment.

Item	*Clitoria ternatea*	*Desmanthus* spp.	*Desmanthus leptophyllus*	*Desmanthus virgatus*	*Macroptilium atropurpureum*	*Macroptilium gracile*	*Stylosanthes hamata*	*Stylosanthes guianensis*	*Stylosanthes scabra*	*Stylosanthes seabrana*
Fertile red basalt site (sown 27 February 2019)										
23 April[A]	18.4a	50.0b	–	–	16.9a	48.4b	53.2b	49.1b	39.1b	75.2c
23 July[A]	12.4a	24.9bc	–	–	16.9ab	25.3bc	36.5cd	30.6c	30.5c	46.7d
23 October[A]	6.0b	18.7cd	–	–	12.6c	1.4a	23.9d	21.0d	24.3d	38.1e
Infertile red earth site (sown 5 February 2020)										
17 March[A]	7.5ab	7.3ab	11.6bc	5.2a	11.3bc	15.8cd	26.4e	–	7.9ab	22.5de

Means represent data pooled across grasses. Means with the same letter within a row are not considered different at the 5% probability level.
[A]Back-transformed data.

rainfall. The assessment years reported herein (2021 and 2023) represent Years 2 and 4 after sowing at the fertile site, and Years 1 and 3 at the infertile site. November–October rainfall totals (approximately 650 mm at the infertile red earth site and 1030 mm at the fertile basalt site) were consistent between years (Fig. 2).

Total growing season herbage yields were high and increased from 2021 to 2023 at both sites. Herbage yields were highest (approximately 6–14 t DM/ha) at the high-fertility site, which had naturally high concentrations of plant-available phosphorus, without phosphorus fertiliser, compared with the infertile site where fertiliser phosphorus had been applied and there was less rainfall (4–6 t DM/ha) (Tables 5–8). Total grass yield was not significantly affected by legume species; sown grasses comprised 40–90% of total herbage yield at the infertile site, but 20–50% at the fertile site where plant populations had declined during the first year.

The highest total sown herbage (grass + legume) yields on both land types were recorded in the plots containing *Stylosanthes seabrana*, the highest-yielding legume at both sites, with other legume yields varying in rank (Tables 6, 8). *S. seabrana* yielded 14 t DM/ha averaged across eight grasses (including one 'not sown'), with the legume comprising 55% of total yield. High legume yields resulted in generally higher total herbage yields, particularly at the fertile site where legumes comprised larger proportions of the herbage. The three *Stylosanthes* spp. were the only legumes to contribute substantially to total herbage yield at the infertile site by 2023, yielding 1.3–2.6 t DM/ha when averaged across all companion grasses, followed by *M. atropurpureum*, which produced 0.9 t DM/ha.

Mean legume yields of each grass × legume combination measured at the end of the 2021 and 2023 growing seasons were used to assess the relative competitive capacity of the grasses and legumes (Figs 3, 4). On the fertile site, mean legume yields of all legumes were low (< 2 t DM/ha) in the year after establishment compared with plots with no sown grass, and particularly low when grown with either *Bothriochloa insculpta* or *Urochloa mosambicensis* (both vigorous stoloniferous grasses) (Fig. 3). Legume yields were low (< 1.4 t DM/ha) for all legumes on the infertile site in the year after establishment (where the grasses were more dominant), with the *Stylosanthes* spp. ranking across the top three when grown with each grass. The *Stylosanthes* yields were lowest when grown with *B. brizantha* (vigorous, clumping habit) and *U. mosambicensis*. Some legumes (notably *S. seabrana* and *C. ternatea* (fertile site) and all three *Stylosanthes* (infertile site) competed well with all grasses by 2023, with the exception of *B. brizantha* at the fertile site. Yield of these more competitive legumes increased between 2021 and 2023.

Feed quality

Legumes varied in leaf and stem proportions and key feed value indices (Table 9). Leaf comprised 30–60% of total dry

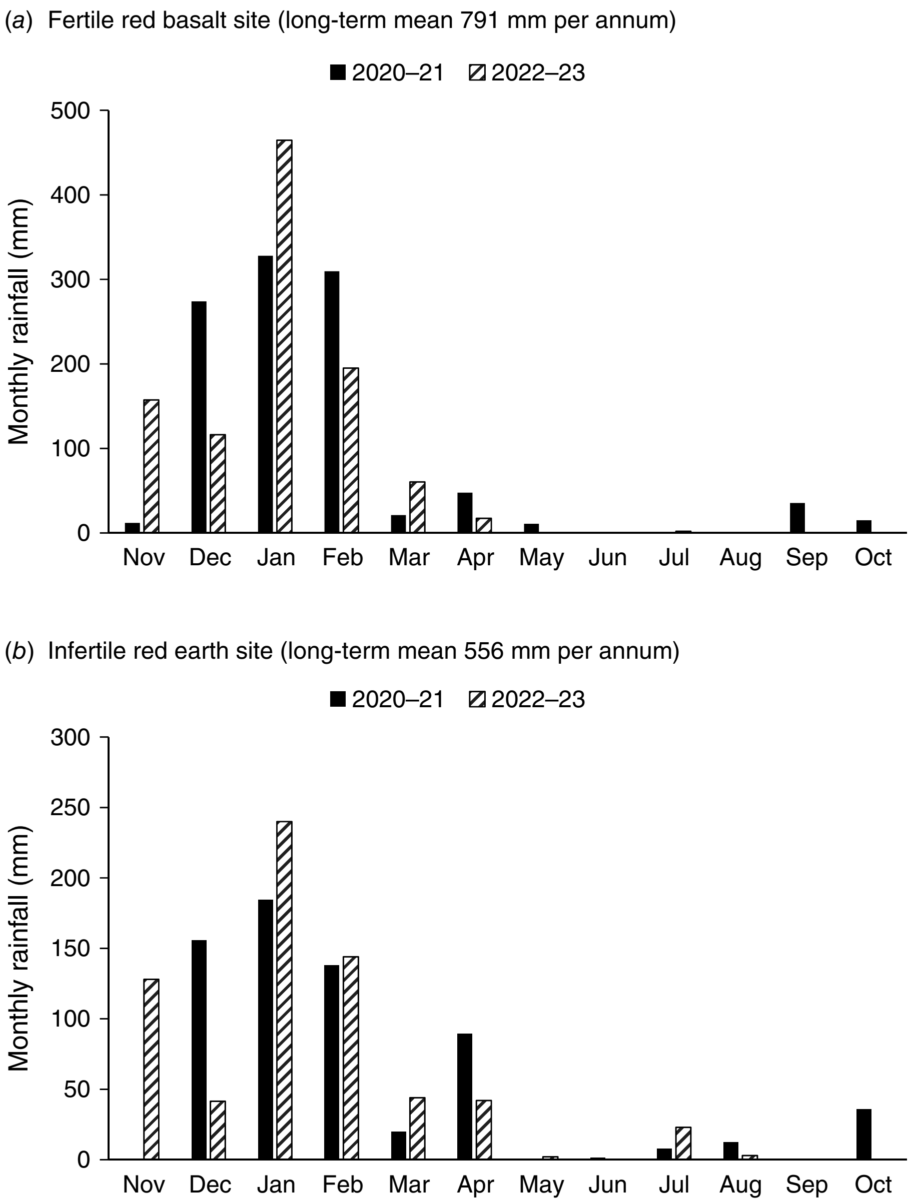

Fig. 2. Total monthly rainfall at the two experimental sites: (*a*) fertile red basalt site and (*b*) infertile red earth site.

matter at the end of the growing season, with shrub legumes (*Desmanthus* sp. and *Stylosanthes* spp.) having values below this (Table 8). Crude protein and metabolisable energy contents also varied between leaf and stem in the wet and dry seasons, and declined over the growing season (Table 9). Dry-season feed-quality values for legume stem were similar to those of companion grasses (data not presented). Dung from the heifers introduced at the fertile site in September 2024 (end of the dry season) had higher crude protein (7.3%) and metabolisable energy (7.7 MJ/kg) than did that from heifers grazing in a similarly spelled undeveloped paddock comprising *Bothriochloa pertusa*, *Themeda quadrivalvis* and *Heteropogon contortus* (4.3% and 7.1 MJ/kg), presumably owing to grazing *S. seabrana* and *C. ternatea*, which had spread across the plots; dietary non-grass (a proxy for legumes and other forbs) was 64% of the diet when the animals were introduced to the grass–legume pasture, declining to 18% after the onset of the wet season, compared with <10% of the diet in the adjacent undeveloped native pasture.

Suppression of opportunist plants

Dominant naturalised grasses and legumes interacted with the sown species in various ways. Increased sown grass and legume yield depressed dominant naturalised grass *B. pertusa* and *T. quadivalvis* yields at the fertile site and *C. rotundifolia* at the infertile site, with yields of <0.1 t DM/h when there was strong competition (Fig. 5). The relationship was particularly strong for *B. pertusa* and *C. rotundifolia*, with high adjusted R^2 values (51% and 71% respectively). Overall, plots containing *B. brizantha, B. insculpta*,

Table 5. Mean total and grass herbage yields of grasses grown with a range of legumes on a fertile red basalt site.

Item	Year	*Bothriochloa insculpta*	*Brachiaria brizantha*	*Digitaria milanjiana*	*Panicum coloration*	*Panicum* hybrid	*Panicum maximum*	*Urochloa mosambicensis*	No sown grass
Total herbage yield (t DM/ha)	2021	5.96bc	8.06d	4.53ab	4.32ab	5.45bc	6.72cd	6.79cd	2.91a
	2023	8.47a	9.42a	6.57a	6.6a	7.33a	6.35a	8.31a	7.28
Grass yield (t DM/ha)	2021	4.54cd	7.05e	3.10b	2.35b	3.68bc	5.56d	5.90de	0.21a
	2023	4.09a	3.77ab	2.20ab	1.37b	1.66ab	2.85ab	3.42ab	0.07c

Means represent data pooled across legumes. Means with the same letter within a row are not considered different at the 5% probability level.

Table 6. Mean total and legume herbage yields of legumes grown with a range of grasses on a fertile red basalt site.

Item	Year	*Clitoria ternatea*	*Desmanthus* spp.	*Macroptilium atropurpureum*	*Macroptilium gracile*	*Stylosanthes hamata*	*Stylosanthes guianensis*	*Stylosanthes scabra*	*Stylosanthes seabrana*
Total herbage yield (t DM/ha)	2021	6.89de	4.47abc	5.75cd	5.94d	4.03a	4.17ab	5.56bcd	7.94e
	2023	9.91b	4.92d	8.46bc	4.83d	5.29d	5.38d	7.48c	14.07a
Legume yield (t DM/ha)	2021	2.28b	0.75a	0.65a	0.01a	0.23a	0.01a	2.66b	5.76c
	2023	3.01b	0.19e	1.21c	0.06f	0.39d	0.04f	2.13b	7.79a
Percentage legume leaf 2021 (%)		43.5a	36.7ab	61.1c	37.6ab	66.2c	33.6a	44.6b	31.3a

Means represent data pooled across grasses. Means with the same letter within a row are not considered different at the 5% probability level.

Table 7. Mean total and grass herbage yields of grasses grown with a range of legumes on an infertile red earth site.

Item	Year	*Bothriochloa insculpta*	*Brachiaria brizantha*	*Digitaria milanjiana*	*Panicum coloration*	*Panicum hybrid*	*Panicum maximum*	*Urochloa mosambicensis*
Total herbage yield (t DM/ha)	2021	2.70a	4.75b	2.86a	2.10a	4.26b	4.11b	2.99a
	2023	4.28bc	5.82a	3.79c	4.18bc	6.11a	4.95abc	5.19ab
Grass yield (t DM/ha)	2021	2.41ab	4.66d	2.60ab	1.76a	4.13d	3.92cd	2.87bc
	2023	3.06bc	5.09a	2.39bc	1.56c	5.16a	2.23bc	3.79ab

Means represent data pooled across legumes. Means with the same letter within a row are not considered different at the 5% probability level.

D. milanjiana or *U. mosambicensis* or *C. ternatea* (fertile site only), *S. scabra* (infertile site) or *S. seabrana* had a low yield of the less desirable plants.

Discussion

The potential for 'production paddock' systems

Results indicated that introduced grass and legume combinations had the potential to substantially improve dry-season forage quantity and quality on both fertile and infertile land types when fertilised with phosphorus and sulfur as required to support legume growth. The 'production paddock' concept, whereby a small proportion of a property is developed, targets higher and earlier sale weights through the improved nutrition of livestock classes used for sale to generate income for business owners. It could also be considered a 'weaner' paddock or 'steer' paddock or be used to improve the nutrition of breeding females. Combined with sound grazing-land management and animal husbandry practices, improved breeding female nutrition could partly address the often low levels of breeder productivity typical of the seasonally-dry monsoonal tropics in northern Queensland, enabling producers to viably carry fewer animals (Rolfe *et al.* 2016). This will be contingent on business owners taking the opportunity to modify their grazing land management rather than simply increase cattle numbers.

The size of the 'production paddock' in the large (20,000–40,000 ha) properties of the study region should ideally be sufficient to feed the cohort of sale animals, but the area will also be determined by the infrastructure of the property and the amount the owner is prepared to invest. Benefits accrue through increased stocking and animal growth rates. Previous modelling for *Stylosanthes* spp. + native grass production paddocks in northern Queensland used 500 ha for comparing the productivity of fertilised and unfertilised *Stylosanthes* spp. paddocks compared with native pastures on an infertile soil (Bowen *et al.* 2019). In its simplest form, 3500 ha of unfertilised *Stylosanthes* was found to be sufficient to raise all of the steers from the 30,000 modelled property at a pasture utilisation rate of 20%. This area could logically be reduced using fertilised *Stylosanthes* paddocks because of higher carrying capacity (30%) and higher growth rates (21%) over unfertilised *Stylosanthes* paddocks. Although these results apply only to one land type, they indicate that a developed area of ~5–10% of a property would be sufficient to substantially improve business performance in the first instance.

Herbage yields and feed quality

The rainfall recorded for the growing periods reported represented long-term mean values for both sites and were conducive for vigorous growth of the grass + legume combinations once established. The preparation of a weed-free and friable seed bed by using cultivation and herbicides, and February sowing by broadcasting tested seeds followed by rolling, resulted in high initial grass and legume populations. At the fertile site, poor follow-up rainfall greatly reduced the grass populations by the end of the dry season, although with less reduction in legume numbers. However, the grasses demonstrated a capacity to recover over the next two growing seasons, yielding 2–6 t DM/ha 2 years after sowing. There was sufficient rainfall at the infertile site to maintain grass and legume populations over the first dry season, and the plots at this site contained a greater proportion of grasses than did those at the fertile site. Overall, grass and legume populations after the establishment year and the high herbage yields were considered sufficient for a competitive interaction between plants. The exception was the one annual legume sown, *M. gracile*, which established well at both sites, but did not recruit sufficient plants from seed to produce useful herbage yields when grown with the grasses.

The annual herbage yields achieved were approximately two to three times those of undeveloped native pastures in good land condition when measured in a rigorous grazing management study completed in the current study region (Ash *et al.* 2011). Those authors reported herbage yields of ~3 t DM/ha for rested pastures on a fertile basalt soil and ~2.9 t DM/ha for rested pastures on a low-fertility red earth soil in analogue years for annual rainfall. The yields achieved in this study were sustained 3–4 years after sowing without additional fertiliser application; so, they can be considered to be representative of established pastures. However, additional application of sulfur or phosphorus is likely to be required to maintain longer-term productivity.

Table 8. Mean total and legume herbage yields of legumes grown with a range of grasses on an infertile red earth site.

Item	Year	*Clitoria ternatea*	*Desmanthus* spp.	*Desmanthus leptophyllus*	*Desmanthus virgatus*	*Macroptilium atropurpureum*	*Macroptilium gracile*	*Stylosanthes hamata*	*Stylosanthes scabra*	*Stylosanthes seabrana*
Total herbage yield (t DM/ha)	2021	3.18a	3.21a	3.24a	3.61a	3.40a	3.34a	3.17a	3.43a	3.98a
	2023	4.62bcd	4.48cd	4.87bcd	4.37d	5.16bc	4.45cd	5.08bcd	5.20ab	5.89a
Legume yield (t DM/ha)	2021	0.02ab	0.01a	0.01a	0.01a	0.08b	0.01a	0.18c	0.35d	0.63e
	2023	0.43d	0.04e	0.03e	0.04e	0.91c	0.10e	1.31b	2.32a	2.60a
Percentage legume leaf (%) (2021)		42.6b	38.0b	38.4b	19.8a	60.4c	54.3c	40.7b	39.9b	26.1a

Means represent data pooled across grasses. Means with the same letter within a row are not considered different at the 5% probability level.

Although not measured, legume nitrogen fixation would also be likely to contribute to improved forage yields.

The standing herbage yields were assessed at the anticipated completion of the growing season on 13 May at the fertile site during 2021, and early to mid-March on all other occasions. These dates are not considered to have affected recorded yields at the fertile site, because rainfall after February was minimal in both years. However, March and April rainfall at the infertile site would likely have prolonged growth, potentially resulting in higher herbage yields if measured later in the year (Fig. 2). Regardless, the high yields of sown grasses and legumes from April onwards matches livestock feed demands when capacity to satisfy these demands from natural pastures is limited (McCown 1981).

Grazing management has a marked effect on pasture composition and growth in the seasonally-dry monsoonal tropics, with periods of rest encouraging the growth of perennial and palatable grasses (Ash *et al.* 2011). In the current study, the plots were spelled during the wet season to provide a 'bank' of feed during the early–mid dry season, and grazed once pasture composition and yield measurements had been completed. Whereas the grazing strategy met the needs of a detailed replicated experiment, a beef producer would be likely to modify the grazing strategy i.e. grazing might be longer in the growing season, or animals might be introduced into the paddock at different times depending on the time of weaning. A short period of wet-season grazing to utilise the high-quality pasture during the wet season might also be employed. The performance of the various grasses and legumes could alter depending on these decisions, but consistency in rankings for yield across the sites with the *Stylosanthes* spp. combining well with a range of grasses indicated that these options could be recommended for testing on a larger scale in the first instance.

In a review of dietary restrictions and options for attaining cattle growth paths from tropical pastures in northern Australia, Poppi *et al.* (2018) described that the challenge to improving animal performance is to find dry-season high-energy or high-protein supplements that can be grown on farm, and pasture legumes provide one strategy to achieve this. The feed value of legume leaf available remained high during the dry season when the feed quality of undeveloped pastures normally declines. The leaves of the most successful legumes (the shrub legumes *S. scabra* and *S. seabrana*) at each site contributed high mean crude protein values (~15%) during the wet and dry seasons, although stem values were low (5–6%). Leaves represented the minority of plant sample biomass during the dry season, with values generally lower for *S. seabrana* (26–31%) than for *S. scabra* (40–45%). The crude protein content of the twining *C. ternatea*, which also performed well at the fertile basalt site, was higher than this (20.2% for leaf and 10.1% for stem), and the percentage of leaf was 42–43%. Metabolisable energy levels of leaf (8–9% MJ/kg DM) also remained high in the dry season compared with stem (~5 MJ/kg DM).

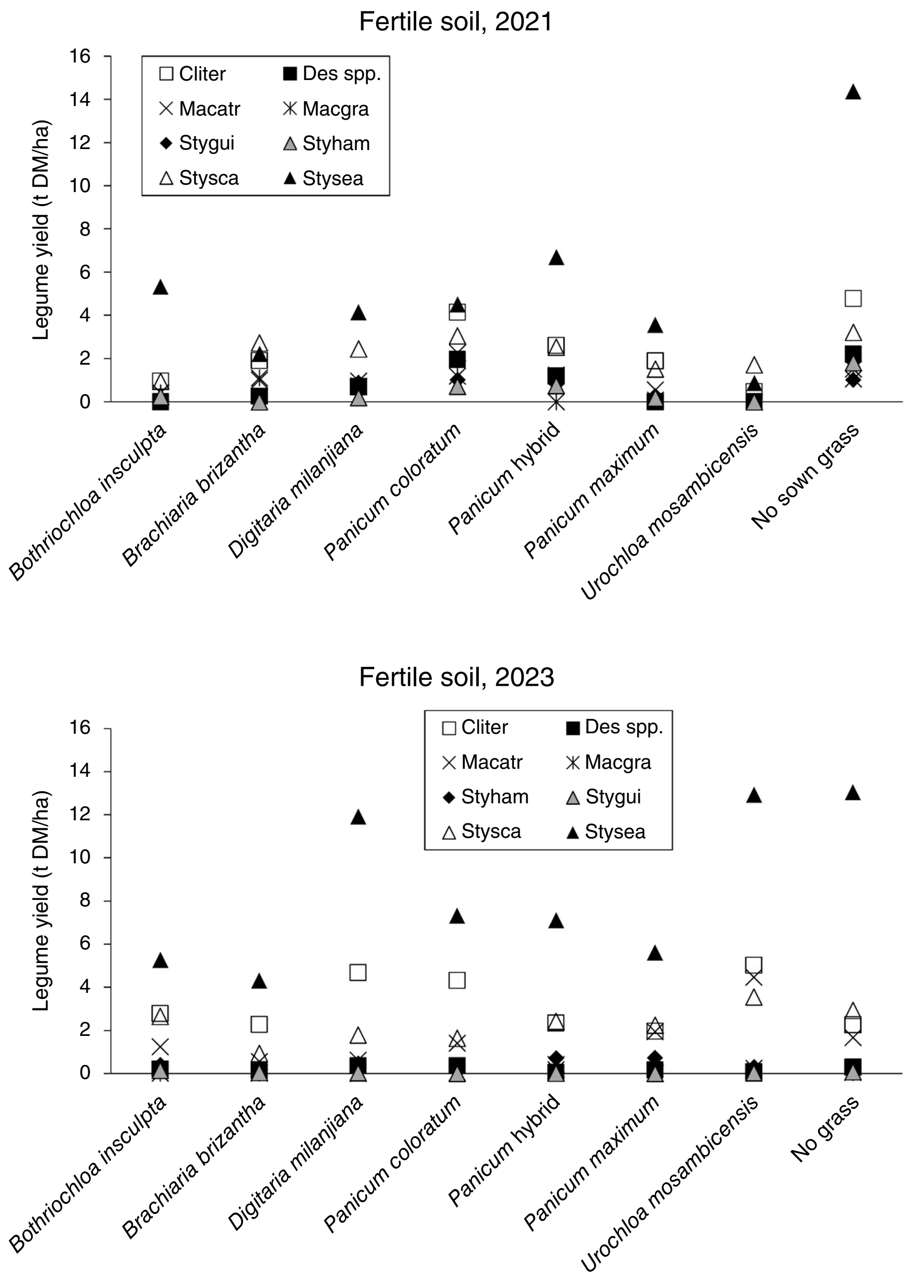

Fig. 3. Mean legume yield (t DM/ha) when grown in combination with different sown grasses on a fertile red basalt soil in northern Queensland (2021 LSD $P < 0.05 = 3.39$; 2023 no measure of variability is presented because back-transformed data are shown).

Notwithstanding the potential benefits to grass production through legume nitrogen fixation and nutrient cycling, these results indicated that legume leaf alone will provide the protein and energy required for cattle growth during the dry season. Diet-quality analysis (FNIRS) of heifer dung sampled in September at the legume-augmented site on the fertile land-type indicated that legume consumption considerably improved dry-season diet quality, particularly crude protein, compared with adjacent native grass pastures.

Potential economic benefits

Using the herbage yields and feed quality of the study, an economic gross-margin analysis compared the performance of the 'production paddock' concept on both land types with undeveloped native grass pastures (Finlay and Cox 2022). Modelling steers from 6 to 18 months, gross margins per hectare after interest by using sown grass × legume combinations were four to seven times those on native pastures when cattle prices and costs were averaged over 5 years. Gross margins were highest at the fertile site, owing to increased herbage production and lower fertiliser cost than at the infertile site. The results support Bowen *et al.* (2019) who recorded similar benefits for legume adoption in native pastures on infertile soils in northern Queensland.

To confirm the economic benefits and refine methods for the establishment and management of production paddocks,

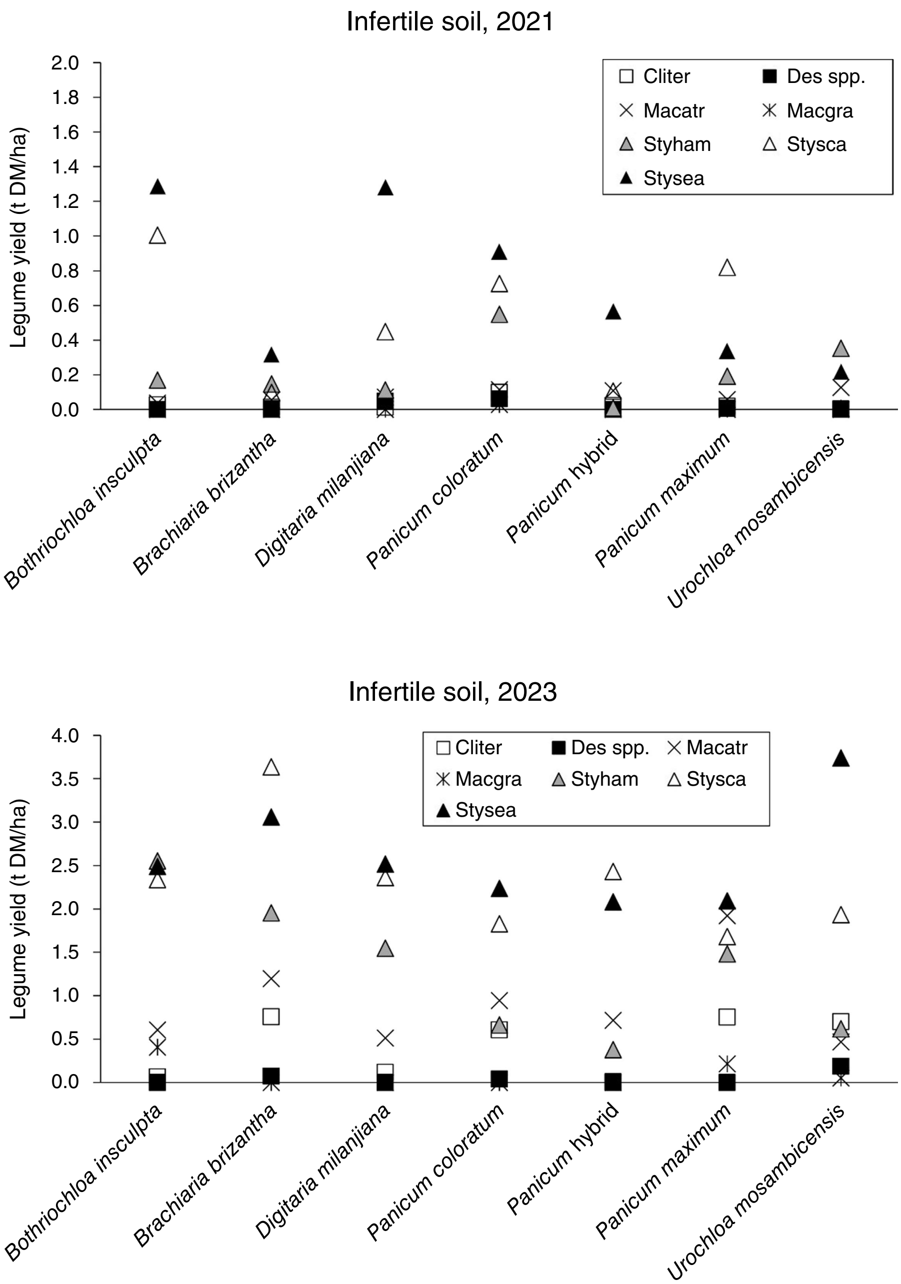

Fig. 4. Mean legume yield (t DM/ha) when grown in combination with different sown grasses on an infertile red earth soil in northern Queensland (2021 LSD $P = 0.051 = 0.11$; 2023 LSD $P < 0.05 = 0.84$).

it is recommended to the northern Australian beef industry that studies and demonstrations be completed at paddock scale to assist decision-making by graziers.

Competition between sown pasture plants and other companion species

Results indicated differing capacities in vigorous grasses and legumes to compete with other plants in an environment (fertility and rainfall) conducive to plant growth. The grasses and legumes tested were introduced taxa known to persist in natural environments with the capacity to spread or recruit new plants from seeds (Cook *et al.* 2020). The experiments clearly demonstrated competition effects, with certain grasses and legumes outyielding others. In particular, *Stylosanthes seabrana*, but also *C. ternatea, M. atropurpureum* and *S. scabra* or *S. hamata* (depending on the site) competed with the dominant grasses *B. insculpta, D. milanjiana* and *U. mosambicensis*.

By the end of the experiment, legume productivity (effectively the established pasture phase) was not overly affected by companion grass populations in the first years of establishment. By 2023, the more successful legumes performed well when originally established with strong grass competition (infertilfe red earth site) or when grown with low levels of grass competition (fertile red basalt site). However, these

Table 9. Mean values for key feed-quality indices from plants sampled in 2021 from small-plot assessments of combinations of sown tropical pasture grasses and legumes conducted at sites on fertile red basalt soils and infertile red earth soils in northern Queensland.

Item	Season		*Clitoria ternatea*	*Desmanthus* spp.	*Macroptilium atropurpureum*	*Macroptilium gracile*	*Stylosanthes hamata*	*Stylosanthes guianensis*	*Stylosanthes scabra*	*Stylosanthes seabrana*
Crude protein (%)	Wet season	Leaf	18.6	14.1	17.3	19.71[A]	16.9	10.2[A]	16.0	16.5
		Stem	12.4	7.10	12.6		11.8		8.00	7.80
	Dry season	Leaf	20.3	16.5	15.7	14.7	17.4	6.49[A]	13.9	15.7
		Stem	10.1	6.00	9.30	8.00	9.70		6.50	6.20
Metabolisable energy (MJ/kg DM)	Wet season	Leaf	8.92	10.4	8.15	9.37[A]	8.83	13.8	9.20	8.68
		Stem	5.38	5.87	5.34		6.81	6.80	4.99	4.87
	Dry season	Leaf	9.04	9.76	8.51	8.94	9.30	8.00	8.53	8.51
		Stem	5.67	5.57	6.59	7.93	7.07	5.23	5.21	5.10

[A]Feed-quality indice represents a whole plant sample.

pastures are young, and changes in grass and legume dominance will occur over time, likely being dependent on grazing strategy.

Assessing potential pasture legumes as grass × legume combinations was important, because some legumes (*Desmanthus* spp. and *M. gracile*), which had performed well previously in monoculture small plots (Cox *et al.* 2019), performed poorly when grown as grass × legume combinations. This may simply be a consequence of different adaptation and growth habit.

An additional benefit of the competitive grass–legume systems was suppression of the undesirable *B. pertusa* and *T. quadrivalvis* (fertile site) and *C. rotundifolia* (infertile site) respectively, lifting or restoring productivity. Repopulation of plots by these species where there was low sown grass + legume biomass, and their almost complete suppression where sown grass + legume yields were high indicates that interplant competition, rather than the thorough site preparation, was largely responsible for the result. Mid- to long-term suppression of such species is essential if the productivity of the production paddock is to be realised and be profitable in the long term. Assessments were conducted only over the first 3–4 years post-sowing, and changes in pasture composition could subsequently occur depending on grazing management and soil fertility. A spell-graze system with pasture composition monitoring would be required for producers to maintain the productivity and competitiveness of these sown grass–legume pastures.

Conclusions

Small-plot assessments have shown that well-adapted, palatable and productive grasses and legumes grown in combination show potential as long-term pastures on red basalt and red earth land types within the seasonally-dry monsoonal tropics of northern Queensland. Benefits to grazing animals would accrue from the high-quality (crude protein and metabolisable energy) forage, particularly during the dry season when feed supply and quality are generally limiting in native pastures. The differing capacities among individual legume species to compete with more competitive grasses when phosphorus and/or sulfur are applied results in a limited suite of potentially suitable legumes for each land type, compared with assessment without companion grasses. The *Stylosanthes* spp., particularly *S. scabra* and *S. seabrana*, are competitive legumes on fertile and infertile soils, whereas *Clitoria ternatea* appears better adapted to fertile soils. Well-adapted and productive grasses and legumes can suppress growth of less desirable but dominant species, but it is unknown whether this advantage will be maintained, and as such requires long-term assessment. On the basis of these small-plot studies, there is an opportunity to improve productivity per grazing animal and overall herd profitability in the seasonally dry tropics by developing

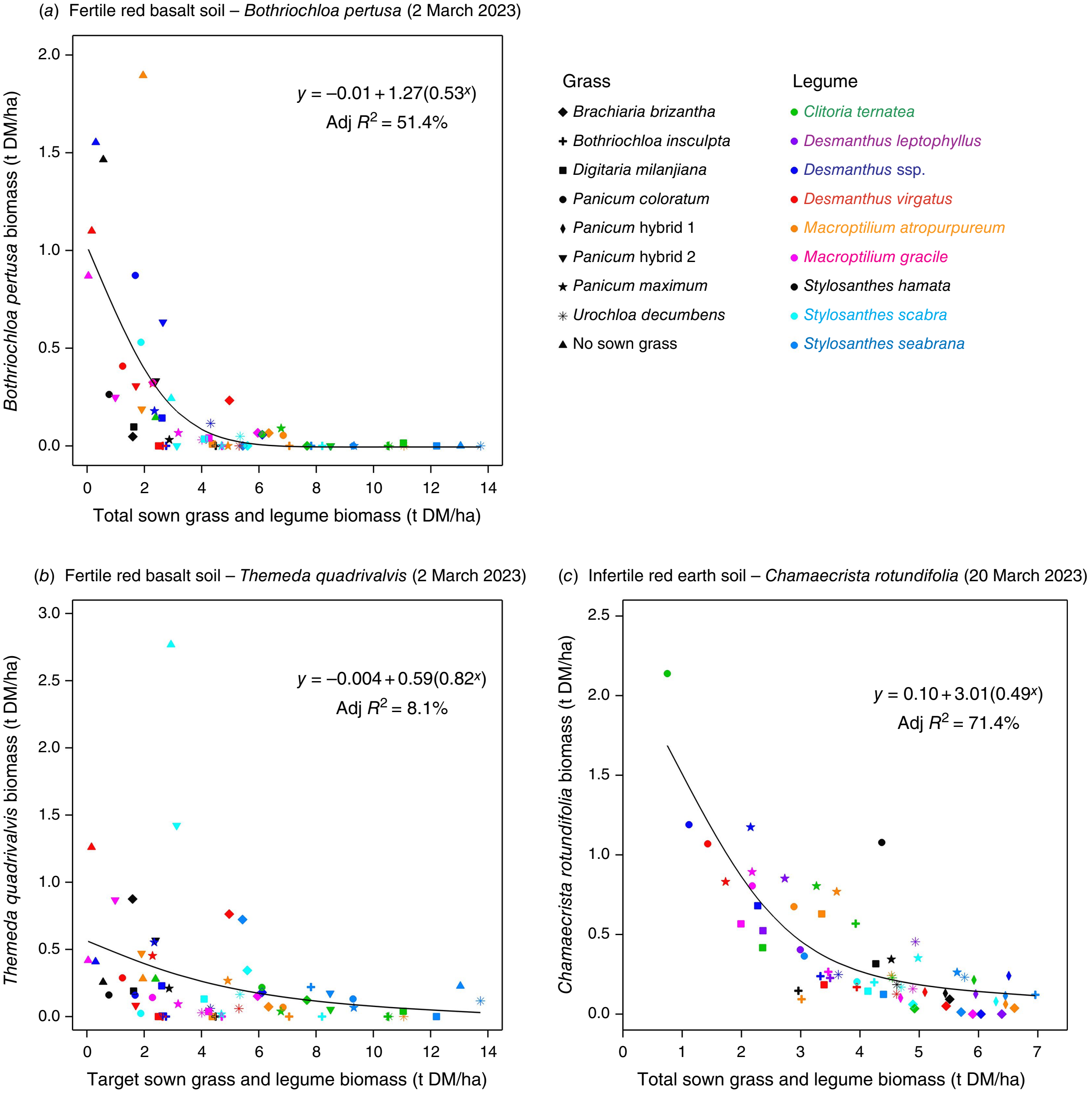

Fig. 5. Regression of the influence of sown grass and legume herbage yield (t DM/ha) on the herbage yield of naturalised low-value plants: (*a*) and (*b*) are low value grasses and (*c*) is a pasture legume of variable utility.

sown grass + legume (particularly *Stylosanthes*) pastures on small areas of properties.

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Data availability. Data pertaining to this research will be available upon request to the corresponding author, subject to approval by the principal research and cofunding agencies.

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