

Reducing enteric methane in northern Australian grazing systems – a synthesis of the role for tropical legumes

Elaine Mitchell^{A,*} , Beverley Henry^A, Gavin Arthur Peck^B , Ed Charmley^C, Peter Grace^A and Richard Eckard^D 

For full list of author affiliations and declarations see end of paper

***Correspondence to:**

Elaine Mitchell
Sustainable Agroecosystems, School of Biological and Environmental Science, Faculty of Science, Queensland University of Technology, Brisbane, Qld, Australia
Email: e5.mitchell@qut.edu.au

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ABSTRACT

Enteric methane (CH₄) emissions from ruminant livestock are a major source of greenhouse gases in northern Australian grazing systems, where the extensive, low-input nature of production limits the applicability of alternative mitigation strategies such as feed additives. Tropical forage legumes therefore represent one of the few practical abatement options available, offering mitigation through both direct suppression of rumen methanogenesis and indirect improvements in animal productivity. This review synthesises evidence from *in vitro*, *in vivo* and farm-scale studies and integrates these findings with production-system modelling and agronomic assessments to evaluate CH₄ abatement potential under extensive grazing conditions. *In vitro* studies demonstrated an average 12.1% reduction in CH₄ yield across tropical legume species, while *in vivo* studies reported a comparable mean reduction of 13.8%. Legume inclusion rate (% of dietary dry matter) emerged as the primary predictor of CH₄ response. Production-system modelling across low-, medium- and high-productivity grazing systems showed that legume incorporation reduced emissions intensity by an average of 28%, with approximately 82% of the reduction attributable to productivity gains and 18% to direct suppression of enteric CH₄. A multi-criteria prioritisation framework combining CH₄ abatement potential with agronomic suitability identified a small number of high-potential species. *Leucaena leucocephala* consistently produced the greatest direct CH₄ suppression, whereas *Desmanthus* and *Stylosanthes* spp. offered broader environmental adaptation and greater scalability despite more modest direct abatement. These findings suggest that effective CH₄ mitigation in northern Australian grazing systems will require a portfolio of legumes tailored to regional conditions. Tropical legumes are an immediately deployable mitigation strategy, although their full potential will depend on overcoming constraints to establishment, persistence and adoption in commercial grazing systems.

Keywords: emissions intensity, enteric methane emissions, greenhouse gas reduction, meta-analysis, Northern Australia, Ruminant livestock, tannins, tropical legumes, tropical pastures.

Introduction

Methane (CH₄) is a potent greenhouse gas with a global warming potential approximately 28 times that of carbon dioxide over a 100-year time horizon. Enteric fermentation in ruminant livestock represents one of the largest anthropogenic sources of CH₄, and reducing these emissions has become a central focus of agricultural climate mitigation strategies (Tedeschi *et al.* 2022). In Australia, CH₄ emissions from livestock account for approximately 10% of total greenhouse gas (GHG) emissions reported in the national inventory, with nearly half attributed to the northern beef cattle industry (Mayberry *et al.* 2019; DGCEEW 2023). As the majority of these emissions arise from grazing animals, reducing enteric CH₄ in extensive pasture-based systems is central to the sector's capacity to contribute meaningfully to Australia's net-zero ambitions by 2050 and to respond to increasing market scrutiny regarding the carbon footprint of exported beef.

Northern Australia's grazing region spans tropical and subtropical environments, including the rangelands of the Kimberley and Pilbara districts of Western Australia, the Northern Territory, and the savannas and pasture systems of Queensland (Fig. 1, Table 1). In 2022, these regions accounted for 8.7%, 7.0%, and 44.2% of Australia's national cattle herd, respectively (MLA 2024). The region is characterised by highly variable rainfall,

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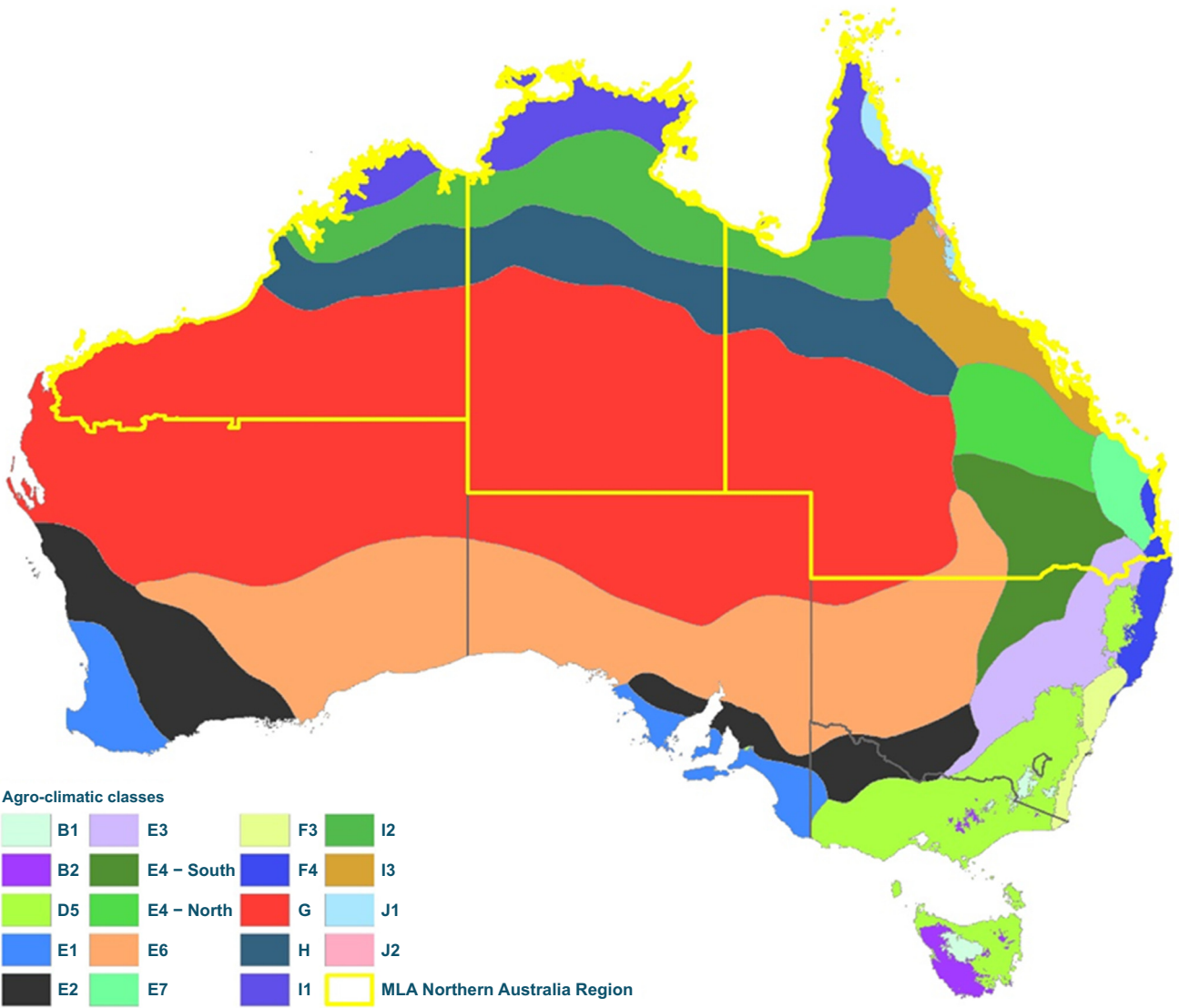


Fig. 1. Northern Australian grazing region and agro-climatic zones of Australia, modified from Hutchinson *et al.* (2005), used to map legume suitability and northern livestock numbers. Modifications include subdividing the Brigalow Belt (E4) into northern and southern components, with the southern portion defined as experiencing an average of ≥ 20 potential frost days per year.

climatic extremes, and generally low soil fertility, although more favourable sub-regions occur (see Supplementary material 1). These constraints favour extensive, low-input production systems with low stocking rates and relatively slow animal growth. Prolonged finishing times increase lifetime CH_4 emissions per animal and contribute to relatively high CH_4 intensity (g CH_4 per unit of beef produced) compared with temperate production systems (e.g. Charmley *et al.* 2008; Poppi *et al.* 2018).

Tropical forage legumes can reduce CH_4 emissions through two complementary pathways: (1) indirect abatement via improved animal productivity; and (2) direct abatement through altered rumen fermentation. Indirect effects arise as legumes enhance pasture quality in grass-dominated systems by fixing nitrogen, increasing pasture production by ~50–100%

in nitrogen-limited environments (e.g. Peck *et al.* 2017), while also improving crude protein concentration and digestibility (e.g. Bishop *et al.* 1983; Coates *et al.* 1997). These changes enhance rumen function and accelerate liveweight gain (LWG), reducing CH_4 intensity by diluting emissions per unit of output (Charmley *et al.* 2008; González *et al.* 2014).

Direct effects occur within the rumen, where altered fermentation pathways and anti-methanogenic secondary compounds can reduce CH_4 production (g CH_4 per animal per day) and CH_4 yield (g $\text{CH}_4 \text{ kg}^{-1}$ dry matter intake) (Tavendale *et al.* 2005; Jayanegara *et al.* 2010; Aboagye and Beauchemin 2019). In this synthesis, CH_4 abatement is considered across three related but distinct metrics: (1) CH_4 production; (2) CH_4 yield; and (3) CH_4 emissions intensity (g $\text{CH}_4 \text{ kg}^{-1}$ LWG). Reductions in CH_4 production or yield

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Table 1. Description of agro-climatic classes relevant for northern Australia. Codes correspond to classes described by Hutchinson *et al.* (2005) (Fig. 1).

Class	Description	Cattle herd ^A
E3	Most plant growth in summer, although summers are moisture limiting. Temperature limits growth in winter.	2%
E4	Growth is limited by moisture rather than temperature and the winters are mild. Growth is relatively even throughout the year. This climate zone aligns with the Brigalow Belt bioregion.	30%
E6	Semi-arid climate that is too dry to support field crops. Soil moisture tends to be greatest in winter.	1%
E7	Moisture is the main limit on crop growth. Growth index lowest in spring. South-east Queensland climate zone.	6%
F4	Warm and wet sub-tropics. High rainfall sub-tropics.	1%
G	Desert, supporting very little plant growth due to water limitation.	18%
H	Semi-arid, with some growth in the warm season but too dry for cropping. These climate zone forms a transition between the monsoonal zone (I) and the arid zone (G).	15%
I1	Strongly developed wet and dry seasons with plant growth determined by moisture availability. 5–6 months growing season.	4%
I2	Temperature and moisture are more seasonal than for I1 and the growing season is shorter (4–5 months).	9%
I3	This has cooler winters than I1 and I2 with a growing season lasting at least 6 months.	13%
J1	Moisture and temperature regime supports growth for 8–9 months of the year, with a 3–4-month dry season.	0.5%
J2	As for J1 but with a shorter dry season.	0.04%
Total northern Australia beef herd		13.3 million

A description of production systems, as determined by agro-climatic classes is in Supplementary material 1.

^AABS (2022).

indicate lower CH₄ emissions per animal or unit of feed intake, respectively, whereas reductions in emissions intensity reflect improved production efficiency. Importantly, lower emissions intensity does not necessarily imply lower absolute emissions, particularly where productivity gains are accompanied by higher feed intake, stocking rates, or total system emissions.

Because more than 90% of ruminant livestock are managed under extensive grazing conditions (Charmley 2025), scalable CH₄ abatement options must be effective within pasture-based systems. Feed additives such as 3-nitrooxypropanol and *Asparagopsis* seaweed have demonstrated substantial CH₄ reduction potential in confined feeding systems (e.g. Hristov *et al.* 2015; Roque *et al.* 2021), but reliable delivery under extensive grazing conditions remains challenging. Emerging approaches, including water-based dosing systems and slow-release boluses (e.g. Chaleat *et al.* 2026) are under development but are unlikely to provide near-term, large-scale solutions. Consequently, pasture-based nutritional strategies (particularly the incorporation of adapted tropical forage legumes) represent one of the most immediately deployable pathways for reducing enteric CH₄ emissions in northern grazing enterprises.

Although both rumen-scale suppression of CH₄ yield and productivity-driven reductions in emissions intensity have been investigated in tropical legumes, these mechanisms are rarely considered together in assessments of abatement potential. In addition, agronomic suitability, environmental adaptation, and adoption potential vary substantially across northern Australia. Integrating these biological and practical dimensions is therefore essential to assess the extent to which legume-based grazing systems can deliver meaningful CH₄ abatement at scale.

This integrated review addresses this gap by evaluating the CH₄ abatement potential of tropical forage legumes in northern Australian grazing systems. Specifically, it: (1) synthesises *in vitro* evidence of CH₄ yield responses; (2) synthesises *in vivo* studies under animal production conditions; (3) reviews relevant farm-scale studies; (4) presents a simple modelling exercise across representative production scenarios in northern Australia (low = 1000, medium = 3000, and high = 5000 kg dry matter (DM) ha⁻¹ per year) to evaluate the impact of legume incorporation (regionally relevant) on emissions yield and intensity; and (5) evaluates agronomic feasibility and adoption potential, including environmental suitability, proportion of the herd affected, productivity under commercial conditions, seed availability, and evidence of industry uptake.

Together, these components provide a systems-level synthesis, integrating processes operating across biological, production, and agronomic domains to evaluate outcomes at the whole-farm and industry level. This integrated perspective helps to clarify the extent to which tropical legumes can deliver practical, scalable CH₄ abatement in northern grazing systems, and their potential contribution to industry decarbonisation targets and global CH₄ reduction commitments.

Materials and methods

This review combines evidence synthesis with original analyses to provide an integrated assessment of CH₄ abatement potential of tropical forage legumes. Review components draw on *in vitro* and *in vivo* studies alongside farm-scale studies, while new analyses extend this evidence through production system modelling across low-, medium-, and high-productivity

zones and an evaluation of agronomic potential. These components are brought together to identify species that achieve a 'sweet spot', where meaningful CH₄ abatement aligns with high agronomic suitability for northern Australian grazing systems.

***In vitro* studies**

A literature search was conducted to identify tropical forages with anti-methanogenic properties, focusing on *in vitro* experiments from both Australian and international studies. These *in vitro* approaches are particularly valuable for high-throughput screening, enabling rapid evaluation and prioritisation of candidate species for subsequent *in vivo* testing.

A database was compiled using systematic searches of Scopus, Google Scholar, and Web of Science. Search terms included 'legumes', 'tropical', 'enteric methane', '*in vitro*', and 'ruminants'. This process identified 15 *in vitro* experiments (20 genera, 32 species) examining the effects of tropical legumes on enteric CH₄ emissions in ruminant livestock (Supplementary material 2). We examined the effect across all studies using the mean relative difference (%) of the legume vs control treatments.

Of the available *in vitro* studies, Durmic *et al.* (2017) provides the most comprehensive evaluation of tropical forage legumes relevant to northern Australia, thereby minimising the methodological inconsistencies that often hinder comparisons across *in vitro* CH₄ studies (Charmley 2025). The study assessed 22 tropical legume and 23 grass species (average of grass species was used at the control) across four seasons, analysing chemical composition using near-infrared reflectance spectroscopy (NIRS) and fermentability via the *in vitro* batch fermentation technique (IVFT), with CH₄ yield expressed as mL CH₄ g⁻¹ dry matter intake (DMI).

The forages tested encompassed a diverse mix of native and introduced species either currently used in northern production systems or identified as promising for these environments. To distinguish true anti-methanogenic effects from differences in overall fermentative activity, such as those arising from lower nitrogen content or reduced digestibility, we standardised CH₄ output to total VFA concentration. This was achieved by calculating the ratio of CH₄ production (mL CH₄ g⁻¹ DM) to VFA concentration (mmol L⁻¹), thereby expressing CH₄ production relative to the extent of rumen fermentation.

***In vivo* studies**

While *in vitro* screening provides a rapid and controlled approach to identify tropical legume species with potential to reduce enteric CH₄ emissions, *in vivo* validation is essential to determine whether these effects are sustained under realistic grazing or feeding conditions. Animal-level studies capture key processes that cannot be replicated *in vitro*, including interactions between diet selection, rumen function, intake regulation, animal metabolism, and growth responses.

We conducted a meta-analysis of *in vivo* trials to identify the overall effect of legume incorporation on CH₄ production

using the following selection criteria: (1) peer-reviewed studies; (2) measurement of enteric CH₄ emissions reported as g CH₄ kg⁻¹ DMI (or a convertible unit); (3) exclusion of studies that did not report the composition of the ruminant diet; (4) inclusion of a control group in which tropical legumes were not fed; and (5) studies featuring legume species suitable for northern Australia.

A total of 23 *in vivo* studies (9 genera, 13 species) met the inclusion criteria (Supplementary material 3), comprising 43 individual observations. Effect sizes were again calculated as the Relative Mean Difference (RMD) in CH₄ emissions between legume and control treatments. To examine sources of heterogeneity, mixed-effects meta-regression models were fitted using the *metafor* package in R (RStudio 2025.05.1). Because several studies reported multiple comparisons (e.g. different treatments, inclusion levels, or time points), study ID was included as a random intercept to account for non-independence among observations within experiments.

Moderator analyses included legume genus, dietary legume inclusion (% of total diet), animal type, country, and CH₄ measurement method as fixed effects. Species was initially considered but replaced by genus to reduce model complexity and improve stability, given the limited number of observations and sparse representation of several species. CH₄ measurement method was simplified to a binary factor (respiration chambers vs other approaches), while country was classified as Australia vs international studies, and animal type as beef cattle, dairy cattle, sheep, or goats.

Models were fitted using restricted maximum likelihood (REML) for parameter estimation, with maximum likelihood (ML) used for likelihood ratio tests to evaluate the contribution of individual moderators by comparing reduced models (with one term removed) to the full model.

Farm-scale studies

Farm-scale analysis draws primarily on two key investigations that assessed the impact of *Leucaena* on whole-farm GHG emissions (Harrison *et al.* 2015; Taylor *et al.* 2016). Both studies monitored LWG in steers grazing either grass-only (control) or *Leucaena*-based pastures in Queensland, Australia, and used these data to model the net farm-scale GHG balance.

Production system modelling

To complement the limited number of empirical farm-scale studies, a simple modelling exercise was undertaken to examine the potential effects of legume inclusion on GHG emissions, and GHG emissions intensity across contrasting production environments in northern Australia.

The framework was designed to isolate the relative contribution of two pathways of CH₄ abatement: (1) indirect reductions arising from improved animal productivity, whereby increases in LWG and stocking rate reduce emissions per unit of

product through improved production efficiency (i.e. CH₄ intensity); and (2) direct reductions resulting from decreases in enteric CH₄ yield.

Baseline production scenarios were defined to represent low-, medium-, and high-productivity grazing systems in northern Australia. The high-production baseline was derived using data from central Queensland (the Brigalow Belt), while the medium- and low-production baselines were derived from northern Queensland production outlined in a report by Queensland Department of Primary Industries (Thompson *et al.* 2026 [under review]).

For each baseline, an improved legume scenario (S1) was defined based on productivity responses reported in Thompson *et al.* (2026) (Fig. 2). Legume inclusion was assumed to increase pasture production, improve diet quality (particularly crude protein), enhance LWG, and support higher stocking rates. In the low-production system, the incorporation of herbaceous legumes (e.g. *Stylosanthes* or *Desmanthus*) increased pasture production from 1000 to 2000 kg DM ha⁻¹ year⁻¹, with LWG increasing to ~120 kg head (hd⁻¹ year⁻¹) and stocking rate to 0.12 animal equivalent (AE) ha⁻¹. In the medium-production system, pasture production increased by ~2100 kg DM ha⁻¹ year⁻¹ (~70%), from 3000 to 5100 kg DM ha⁻¹ year⁻¹, with LWG rising to ~170 kg hd⁻¹ year⁻¹ and stocking rate to 0.50 AE ha⁻¹. In the high-production system, a *Leucaena*-grass pasture was assumed, increasing pasture production by ~1800 kg DM ha⁻¹ year⁻¹ (~36%), from 5000 to 6800 kg DM ha⁻¹ year⁻¹, with LWG increasing to 235 kg hd⁻¹ year⁻¹ and stocking rate to 0.91 AE ha⁻¹.

A second scenario (S2) incorporated direct CH₄ abatement in addition to the productivity responses represented in S1. In the low- and medium-production systems, *Desmanthus* was assumed as the representative legume, with a 2.2% reduction in enteric CH₄ based on the mean response observed across species from the *in vivo* dataset compiled in this study. In the high-production system, *Leucaena* was assumed, with a 22% reduction in enteric CH₄. This structure enabled separation of productivity-driven (indirect) reductions in emissions intensity from direct reductions in CH₄ yield, as well as their combined effects. It was assumed that legume inclusion in the diet was sufficient to achieve the expected CH₄ response.

Greenhouse gas emissions were then estimated using the Beef GHG Accounting Framework (SB-GAF, seasonal V2.5) developed by the University of Melbourne Primary Industries Climate Challenges Centre (Lopez *et al.* 2024). The SB-GAF is a static pre-farm to farm-gate model (ISO 14040), with scope 1 and 2 emissions calculated using the IPCC-approved Australian national inventory methodology (DCCEEW 2023). The model estimates enteric CH₄ emissions, manure CH₄ and N₂O emissions, and indirect N₂O emissions associated with leaching, runoff, and ammonia volatilisation. Grazing area was held constant across all scenarios to isolate the effect of productivity improvements on emissions intensity. The analysis focused on growing cattle rather than breeder herds to isolate treatment effects; although breeder systems

are important for whole-farm accounting, their inclusion would add complexity without materially altering relative comparisons among pasture scenarios. Soil organic carbon was not included in this analysis (see Supplementary material 5 for justification). A full description of model inputs and outputs is in Supplementary material 4.

The production system modelling was designed to provide a comparative assessment of direct and indirect abatement pathways, rather than to generate precise predictions, and to produce indicative estimates of CH₄ abatement potential.

Assessing the agronomic potential of different legumes in northern Australia

To assess regional potential and agronomic suitability for contributing to enteric CH₄ abatement, each species was assigned a rating of high, medium, low, or very low (Table 2). Ratings were determined using a qualitative framework that integrated an assessment of: (1) climatic suitability across northern Australian agro-climatic zones; (2) the proportion of the northern beef herd located within those zones; (3) long-term persistence and productivity in commercial pastures or experimental trials; and (4) commercial viability, including seed availability and evidence of industry adoption. Ratings were informed by expert knowledge and long-term pasture evaluation trials conducted in northern Australia (e.g. Bell *et al.* 2016), and supplemented by extension including focus group and industry experience (e.g. Peck *et al.* 2011, 2017; Matthews *et al.* 2026).

Given the substantial variation in soil types across northern Australia, greater emphasis was placed on climatic suitability at the regional scale. Broad patterns of suitability were aligned with the agro-climatic zones described by Hutchinson *et al.* (2005) (Fig. 1). In major production regions such as the Brigalow Belt (Class E4), which supports approximately 30% of the northern beef herd (Table 1), the assessment was further informed by targeted industry engagement, including focus group evaluations (Peck *et al.* 2011).

Livestock distribution across climatic zones was quantified using agricultural census data (ABS 2022). Cattle numbers were allocated to agro-climatic zones based on Local Government Area boundaries, and where statistical areas overlapped multiple zones, livestock numbers were proportionally distributed according to land area within each zone. Animals in feedlots were excluded from the analysis; however, as feedlot cattle comprise approximately 4% of the northern herd (ABARES 2024), their exclusion had minimal influence on regional-scale conclusions.

Species were rated as having high potential where they were climatically suited to zones containing a large proportion of the northern herd, had demonstrated strong long-term persistence and productivity, and had established commercial seed supply and industry adoption. Species were classified as medium potential where suitability was restricted to smaller production zones or where moderate persistence or

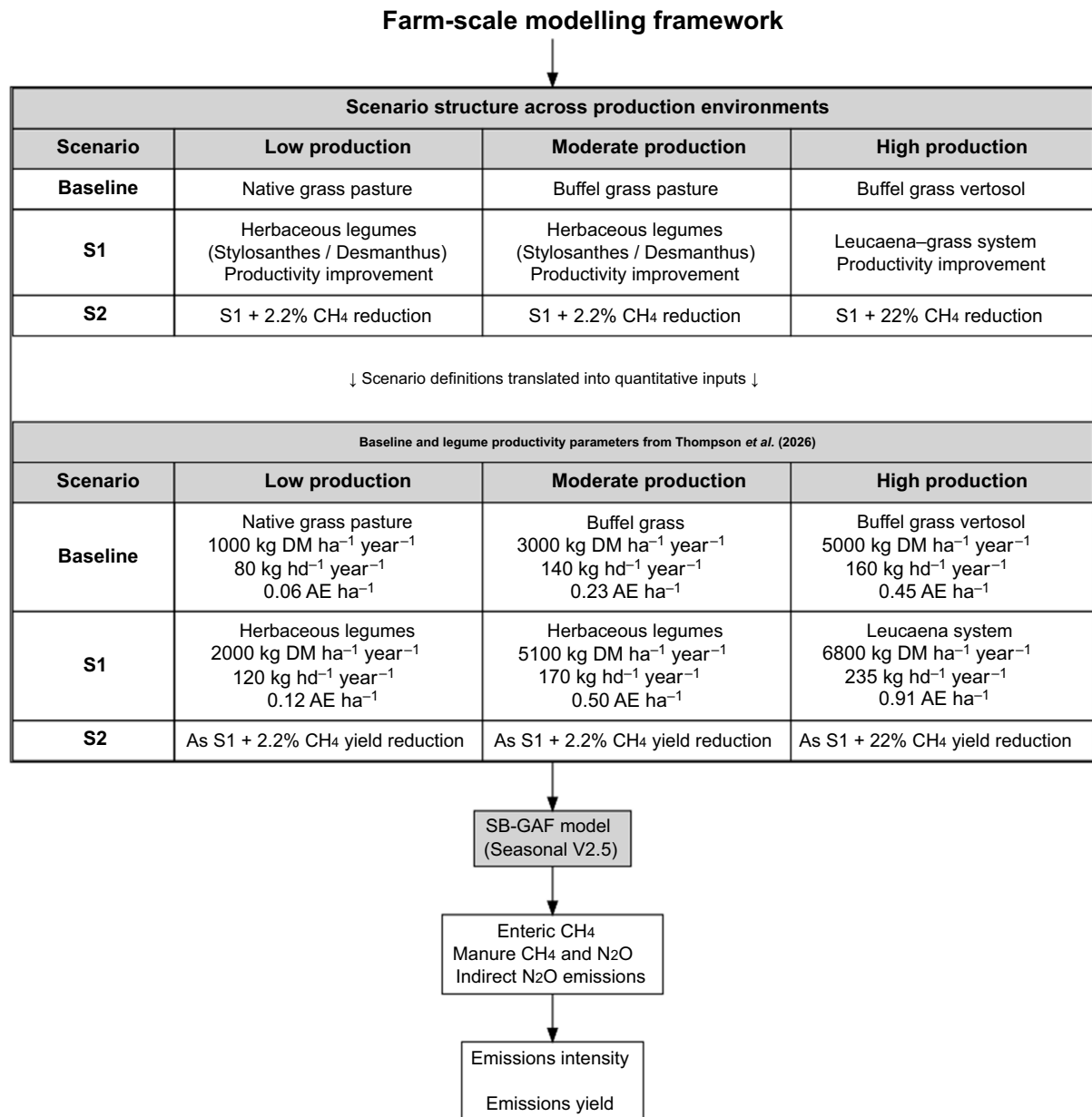


Fig. 2. Farm-scale modelling framework and input parameters used to evaluate the effects of tropical forage legumes on greenhouse gas emissions in northern Australian grazing systems. Three baseline production environments (low, moderate, and high productivity) were defined, with two legume scenarios applied to each system. Scenario 1 (S1) represents productivity responses to legume inclusion, including increased pasture production, liveweight gain and stocking rate based on values from Thompson et al. (2026). Scenario 2 (S2) incorporates these productivity responses and applies direct reduction in CH₄ yield, with a 2% reduction for low and medium productivity systems (based on *in vivo* Desmanthus results) and a 22% reduction for high productivity systems (reflecting Leucaena responses observed in the *in vivo* dataset compiled in this study). Scenario inputs were used in the Seasonal Beef Greenhouse Gas Accounting Framework (SB-GAF v2.5) to estimate greenhouse gas emissions and derive emissions intensity and emissions yield.

adoption constraints were evident. Low potential ratings were assigned where climatic suitability was narrow, persistence was limited, or commercial availability was constrained. A very low rating was applied where seed was not commercially available or adoption had effectively ceased, indicating negligible likelihood of implementation at regional scale.

Legumes used primarily as short-term pastures, fodder crops, or hay species were excluded from the ratings. Although some short-duration legumes can generate high forage yields in 1–5 years, their reliance on regular re-sowing limits their practicality for widespread adoption in extensive northern grazing systems. Because sustained dietary inclusion over the

Table 2. The agronomic potential of legume species to impact methane emissions of the northern Australian beef industry.

Legume ^A	Common name	Climate zone ^B	% of herd	CH ₄ reduction rating	Comments on suitability
<i>Desmanthus virgatus</i>	Desmanthus	I1, I2, I3, H, E3, E4-N, E4-S, E7	79%	High	Mainly suited to alkaline clay soils
<i>Stylosanthes seabrana</i>	Caatinga stylo	I1, I2, I3, H, E4-N, E4-S, E7	77%	High	Suited to a wide range of soils (sandy loam to clay soils)
<i>Stylosanthes scabra</i>	Shrubby stylo	I1, I2, I3, H, E4-N, E7	64%	High	Suited to sandy to loamy soils
<i>Leucaena leucocephala</i>	Leucaena	I1, I2, I3, E4-N, E4-S, E7	62%	High	Suited to fertile soils with high water holding capacity or free draining soils in high rainfall zone; some climate zones have relatively small areas of suitable soils
<i>Stylosanthes hamata</i>	Caribbean stylo	I1, I2, I3, E4-N	43%	High	Suited to sandy to loamy soils
<i>Desmanthus leptophyllus</i>	Desmanthus	E7, I3, E4-N	42%	Medium	Mainly suited to alkaline clay soils. Commercial varieties have not been widely persistent in pastures. Other large statured <i>Desmanthus</i> spp. have a similar geographic range and persistence.
<i>Chamaecrista rotundifolia</i>	Roundleaf cassia (cv Wynn)	I1, I2, I3, E7	32%	Medium	Mixed results: considered useful in some locations, in others unpalatable and weedy
<i>Medicago</i> (multiple spp.)	Annual medic	E3, E4-S	15%	Medium	In northern Australia suited only to frosty inland areas of southern Queensland; temperate annual legume widely used in southern Australia
<i>Centrosema pascuorum</i>	Centro, centurian	I1, I2	13%	Low	Mainly used as fodder crop, hay in monsoonal locations; not widely persistent
<i>Medicago sativa</i>	Lucerne	STP, E3, E7	8%	Very low	Does not persist in the long-term; used as a short-term pasture and hay crop in southern Queensland
<i>Listia bainesii</i>	Lotononis	J1, J2, F4, E7	8%	Very low	Seed not available commercially due to very small seed size constraints for commercial use; suited to sandy soils with low grass competition
<i>Stylosanthes guianensis</i> var. <i>intermedia</i>	Fine-stem stylo	E7	6%	Very low	Seed available only in some years over the past two decades; suited to a narrow climate and soil range (sandy soils, sub-tropics without high grass competition)
<i>Stylosanthes guianensis</i> var. <i>guianensis</i>	Common stylo	J1, J2, F4	2%	Low	Suited to high rainfall zones only; low percentage of herd
<i>Neonotonia wightii</i>	Glycine	J1, J2, F4	2%	Low	Suited to high rainfall zones only; low percentage of herd
<i>Vigna parkeri</i>	Creeping vigna	J1, J2, F4	2%	Low	Suited to high rainfall zones only; low percentage of herd
<i>Aeschynomene villosa</i>	Villose jointvetch	J1, J2, F4	2%	Very low	Seed not available commercially; Suited to high rainfall zones only
<i>Aeschynomene falcata</i>	Jointvetch	J1, J2, F4	2%	Very low	Seed not available commercially; Suited to high rainfall zones only
<i>Arachis pintoi</i>	Pinto peanut	J1, J2, F4	2%	Very low	Seed not available commercially; Suited to high rainfall zones only
<i>Desmodium intortum</i>	Greenleaf desmodium	J1, J2, F4	2%	Very low	Not widely used; suited to high rainfall zones only
<i>Desmodium uncinatum</i>	Silverleaf desmodium	J1, J2, F4	2%	Very Low	Not widely used; suited to high rainfall zones only
<i>Calliandra calothyrsus</i>	Calliandra	J1, J2, F4	2%	Very low	Suited to high rainfall zones only; no cultivars formally released; not grown commercially for pastures in Australia
<i>Aeschynomene americana</i>	American joint vetch	J1, J2	1%	Low	Suited to high rainfall zones only; low percentage of herd
<i>Centrosema molle</i>	Centro	J1, J2	1%	Low	Suited to wet tropics; low percentage of herd; seed available most years
<i>Clitoria ternatea</i>	Butterfly pea	STP (E4-N)	0%	Low	Not persistent under grazing with grass in commercial pastures except on basalt derived, cracking clay soils in Central Highlands (Qld); short-term persistence elsewhere

Ratings were determined using a qualitative framework that integrated an assessment of: (1) climatic suitability across northern Australian agro-climatic zones; (2) the proportion of the northern beef herd located within those zones; (3) long-term persistence and productivity in commercial pastures or experimental trials; and (4) and commercial viability, including seed availability and evidence of industry adoption.

^AThree species of *Macroptilium* (*Macroptilium atropurpureum*, *Macroptilium bracteatum*, *Macroptilium lathyroides*) were considered but excluded from this analysis because of suitability only for short-term pastures.

^BClimate zone codes are mapped in Fig. 1.

lifetime of the animal is required to achieve meaningful regional-scale CH₄ mitigation, only species demonstrating long-term persistence in commercial pastures were included in the assessment.

Integrated synthesis of methane abatement potential

To integrate the evidence synthesised in this review, we developed a multi-criteria prioritisation framework that combines quantitative estimates of CH₄ abatement with more qualitative measures of agronomic suitability. Abatement efficacy was derived from *in vivo* and *in vitro* effect sizes, expressed as the mean RMD (%) in enteric CH₄ emissions for each species. Where both data types were available, *in vivo* responses were prioritised; where only one data type was available, that estimate was used directly. These estimates were interpreted alongside agronomic suitability ratings (high, medium, low, very low).

The synthesis was restricted to species for which both CH₄ abatement data (*in vivo* and/or *in vitro*) and agronomic assessments were available, resulting in 15 species included in the framework. Species were plotted according to CH₄ abatement potential (RMD, %) and agronomic suitability, enabling identification of candidates occupying a 'sweet spot' where abatement efficacy and agronomic feasibility converge. While effect sizes were derived from heterogeneous experimental conditions and agronomic ratings incorporate qualitative components, the approach provides a transparent and systematic basis for identifying frontrunner species for further evaluation and investment. This framework is intended as a structured prioritisation tool rather than a definitive ranking.

Results

In vitro studies

In vitro studies identified substantial variation among tropical legume species in their effects on CH₄ production (Fig. 3). Screening conducted by Durmic et al. (2017) on legume species suitable for northern Australian pastures showed that *Desmanthus leptophyllus* (cv. JCU1) produced the greatest reduction in CH₄ production (27%), whereas *Stylosanthes hamata* (cv. Verano) showed the least, producing 32% more CH₄ than the control. Other species showing CH₄ reduction potential included *Calliandra calothyrsus*, *Leucaena leucocephala* (cv. Tarramba), *Desmanthus bicornutus* (cv. JCU4), *Gliricidia sepium*, and *Desmanthus virgatus* (cv. Marc), with an average reduction of 12.1% across all species and cultivars.

The strong CH₄ reduction potential of *L. leucocephala* observed here is consistent with previous studies reporting reductions ranging from 12 to 44% (e.g. Tan et al. 2011;

Meale et al. 2012; Soltan et al. 2013; Archimède et al. 2016; Albores-Moreno et al. 2020). Methane reductions for *Desmanthus* cultivars have also been reported by Vandermeulen et al. (2018), who observed reductions of 6–24% for JCU1, JCU2, and JCU4. Evidence of anti-methanogenic effects has also been reported for *C. calothyrsus* (Hess et al. 2008), and *G. sepium*, with reductions ranging from 8% to 38% (Meale et al. 2012; Rira et al. 2015).

Variation was evident not only among genera but also among species. For example, *Desmanthus* ranged from an 8% reduction in CH₄ for *D. virgatus* to a 27% reduction for *D. leptophyllus*, while *Stylosanthes* species ranged from a 2% reduction for *Stylosanthes seabrana* to a 32% increase for *S. hamata*. These results highlight the highly species-specific nature of *in vitro* CH₄ responses.

In vivo studies

Across the *in vivo* literature, tropical legume inclusion reduced enteric CH₄ emissions by an average of 13.8% relative to control diets (s.e. = 2.66, $P < 0.0001$). However, substantial heterogeneity among studies indicated that the magnitude of CH₄ reduction varied considerably across experiments (Fig. 4).

To explore this variation, moderator analyses were conducted using mixed-effects meta-regression. Dietary legume inclusion emerged as the dominant predictor of CH₄ response, with each one-percentage-point increase in legume inclusion associated with an additional 0.34 percentage-point reduction in CH₄ emissions (estimate = -0.3435 ± 0.01 s.e., $z = -34.37$, $P < 0.0001$), indicating a strong dose–response relationship. The full moderator model was highly significant overall (QM = 1258.89, df = 14, $P < 0.0001$).

Likelihood ratio tests comparing reduced and full models (fitted using ML) indicated that moderators contributed to model fit in the following order of importance: legume dose, genus, animal type, country, and CH₄ measurement method. Legume dose was by far the strongest moderator (LRT = 1180.14, $P < 0.0001$), followed by genus (LRT = 77.84, $P < 0.0001$). Animal type explained a smaller but significant component of variation (LRT = 7.40, $P = 0.0247$), whereas country and CH₄ measurement method did not significantly improve model fit (LRT = 2.63, $P = 0.105$; LRT = 0.86, $P = 0.355$, respectively).

Misalignment between *in vitro* and *in vivo* CH₄ responses was evident for several species, with RMD generally greater in *in vitro* experiments (Supplementary material 6). This likely reflects methodological differences, as *in vitro* studies typically evaluate substrates at 100% inclusion, whereas *in vivo* diets incorporate legumes as only a proportion of the total ration. Species such as *Desmodium intortum* (–15% *in vivo* vs –43% *in vitro*) and *D. leptophyllus* (–2.2% *in vivo*; –25.4% *in vitro*) exhibited substantially weaker reductions under *in vivo* conditions. In contrast, *L. leucocephala* and *G. sepium* showed closer agreement between experimental

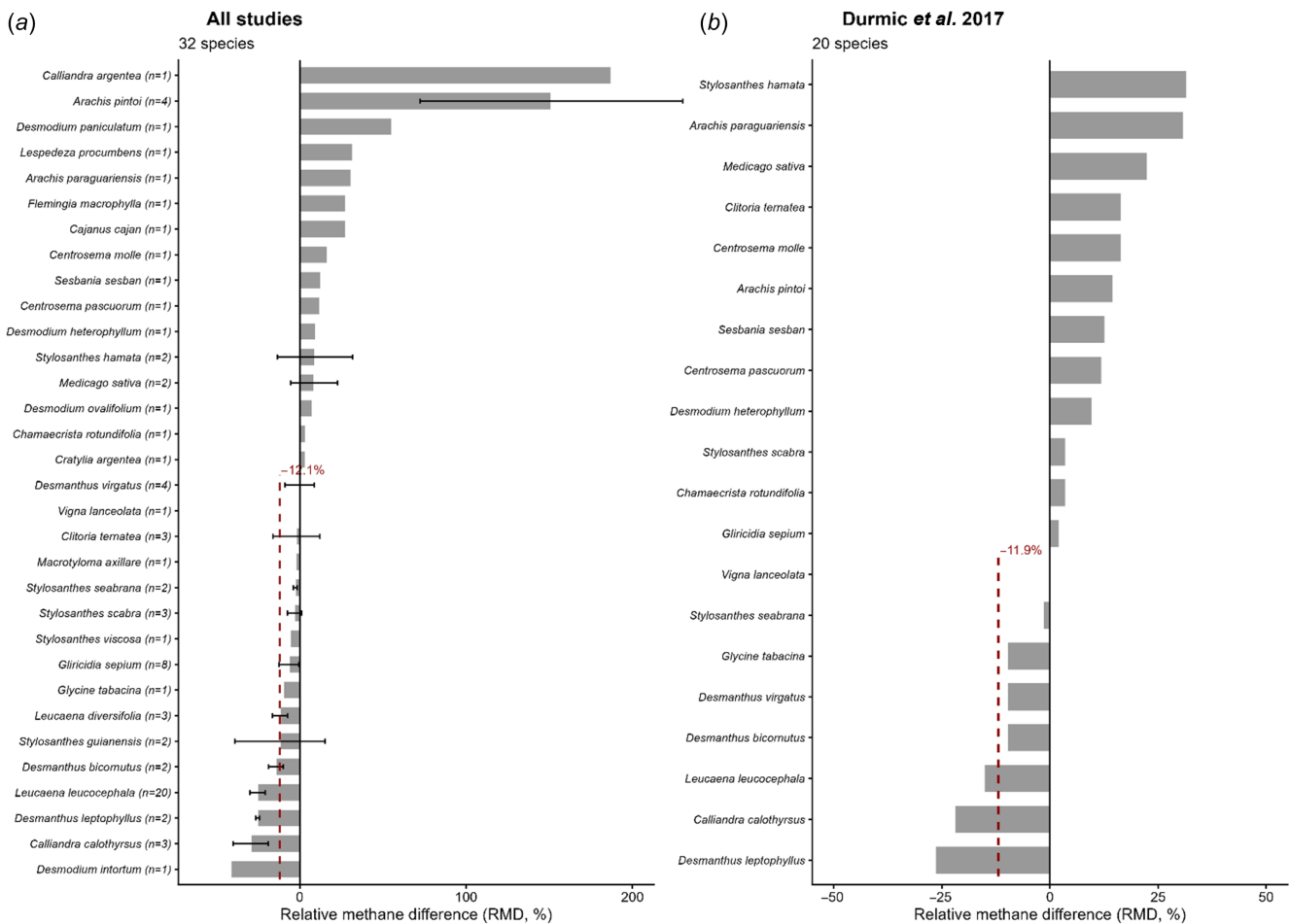


Fig. 3. *In vitro* methane (CH_4) production expressed as relative mean difference (RMD, %) compared with control treatments. (a) Mean CH_4 response across all *in vitro* studies ($n = 15$; 32 species). (b) Results from Durmic *et al.* (2017) shown separately (20 species), as this study provides the most relevant assessment of species suited to northern Australian grazing systems and applies a single, internally consistent methodology, thereby avoiding methodological variation among studies. Dashed red line indicates the mean CH_4 response across species showing a reduction in CH_4 production (negative RMD values).

approaches (e.g. for *L. leucocephala*, -21.9 *in vivo*; -25.4 *in vitro*).

Farm-scale studies

Among the reviewed studies that determine CH_4 abatement due to inclusion of legumes in feed for northern livestock, Harrison *et al.* (2015) offer some of the most relevant insights, focusing on the integration of *L. leucocephala* into subtropical and tropical beef farming systems. The improvement of native pasture with legumes was modelled to increase the CH_4 production by 24% (due to a 21% increase in number of animals) but resulted in a 14% reduction in CH_4 intensity ($\text{kg CO}_2\text{e kg}^{-1}$ beef produced). This reduction in CH_4 intensity was attributed to productivity gains (with an average daily gain, ADG, of 0.9 kg day^{-1} in *Leucaena*-grass pastures vs 0.6 kg per day in Rhodes grass pastures) and the anti-methanogenic effects of *Leucaena* (8.4% less CH_4 with access to *Leucaena* and companion pasture in comparison

to cattle grazing Rhodes grass alone). Similar weight gain rates have been documented by Charmley *et al.* (2023) for *Leucaena* cultivars like Redlands ($0.78 \text{ kg hd}^{-1} \text{ day}^{-1}$) and Wondergraze ($0.81 \text{ kg hd}^{-1} \text{ day}^{-1}$).

A study by Taylor *et al.* (2016) offers similar insights for beef cattle grazing irrigated *L. leucocephala* in northern Australia. Overall, a $\sim 50\%$ reduction in emissions intensity with the incorporation of *Leucaena* was modelled. A point of difference in Taylor *et al.* (2016) from Harrison *et al.* (2015) was the consideration of SOC sequestration ($5 \text{ tonnes C ha}^{-1}$ over 100 years) and the extended timeframe over which the modelling analysis was projected (2000–2100).

Production system modelling

Across all production systems, incorporation of tropical legumes (Scenario 1) substantially increased pasture productivity and stocking rates, resulting in a 2.6-fold increase in total farm GHG emissions relative to baseline systems (Fig. 5). Despite

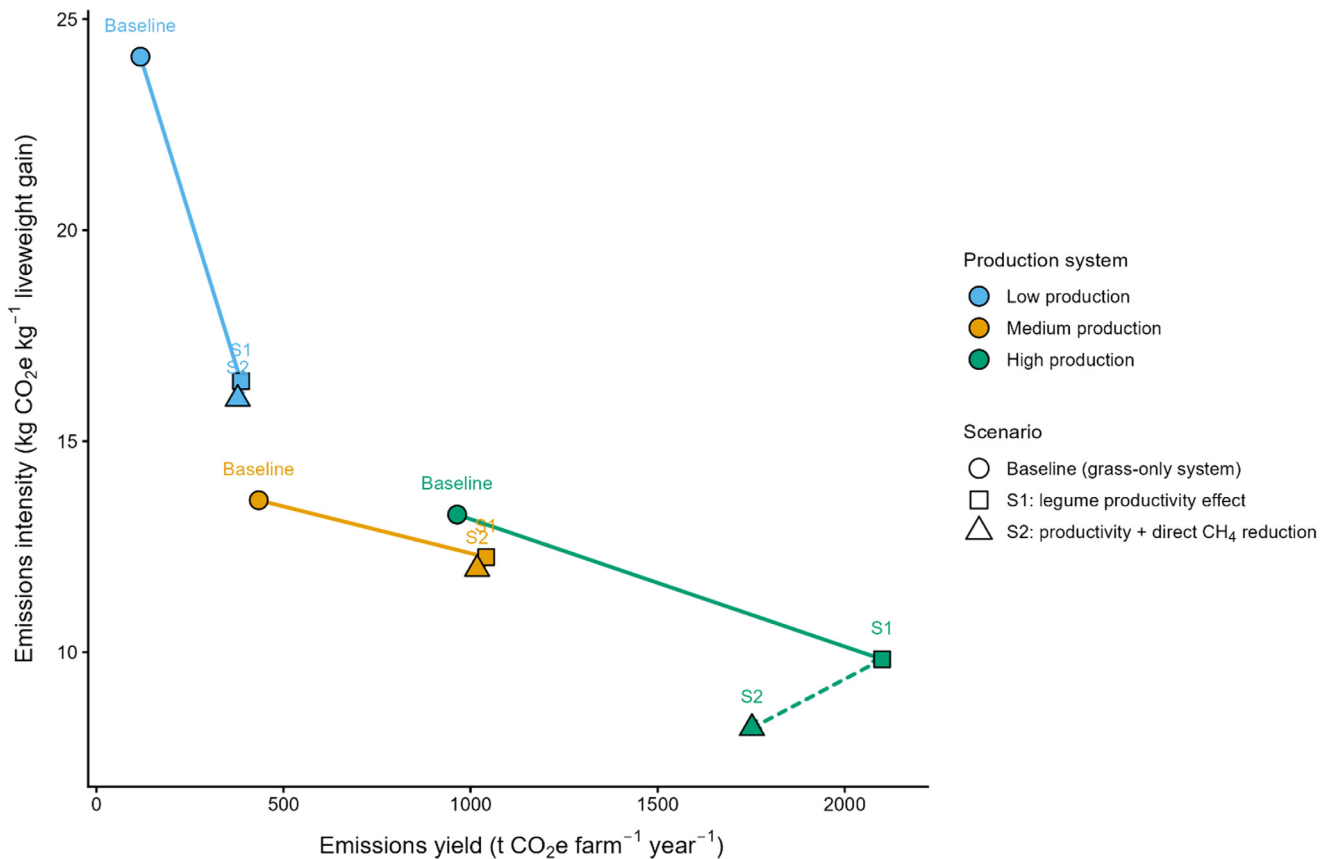


Fig. 5. Relationship between emissions yield (t CO₂e farm⁻¹ year⁻¹) and emissions intensity (kg CO₂e kg⁻¹ liveweight gain) across low-, medium-, and high-production grazing systems. Baseline represents grass-only systems, S1 represents the productivity effect of legume incorporation, and S2 represents the additional effect of direct enteric CH₄ reduction. Solid arrows indicate the shift from Baseline to S1 (indirect productivity effect), while dashed arrows indicate the additional shift from S1 to S2 (direct CH₄ inhibition). Colours denote production systems.

Stylosanthes species; (3) *S. seabrana*; (4) *S. scabra*; and (5) *S. hamata*.

Three additional legumes were classified as having medium potential (*D. leptophyllus*, *Chamaecrista rotundifolia*, and *Medicago* spp.), reflecting constraints to long-term persistence due to climatic adaptation, and occurring in regions supporting approximately 15–42% of the herd (Table 2). The species assessed as having medium CH₄ reduction potential are less widely adapted to the climate zones of northern Australia and/or have a narrower range of suitable soils within climate zones where they are suited. *D. leptophyllus* has been considered a promising species in evaluation programs, but varieties released to date have not shown strong persistence in long-term trials or commercial paddocks over wide geographic areas (Peck *et al.* 2022a). Further research may lead to a more widely adapted variety or management options to improve the performance of this species in commercial pastures. Similarly, other larger-statured *Desmanthus* species (e.g. *D. bicornutus* and *D. pernambucanus*) have exhibited comparable persistence challenges in field trials (Peck *et al.* 2022a). Round-leaf cassia (*C. rotundifolia*) is moderately

widely adapted, but its performance is location dependent, with suitability also strongly influenced by soil type as it is restricted to sandy soils in lower-rainfall environments but tolerates a wider range of soils in higher-rainfall areas. While round-leaf cassia is palatable and useful in some locations, it is considered unpalatable and weedy in others (O’Gara 2005). Annual medics from multiple *Medicago* species are well suited to a range of soils in southern inland Queensland, which carry 15% of the herd across southern Australia and therefore are important at the national scale. Their CH₄ reduction potential is described in Badgery *et al.* (2023).

A total of 19 species were classified as having low or very low industry-scale potential. These species are either restricted to wet tropical or high-rainfall sub-tropical environments that support only ~2% of the northern beef herd, or are limited by practical constraints such as poor persistence under grazing or lack of commercial seed availability. Notably, two agro-climatic zones (Zone G and Zone E6), which together support approximately 20% of the northern beef herd, currently have no commercially released legumes suited to grazing systems. These regions present significant establishment

challenges due to unreliable rainfall and low pasture productivity.

When agronomic suitability is considered alongside CH₄ responses, clear mismatches emerge between experimental abatement potential and field applicability. Several species demonstrating strong CH₄ reduction experimentally (e.g. *C. calothyrsus* and *D. intortum*) are restricted to high-rainfall environments with limited relevance to the northern beef industry, while others (e.g. *Arachis pintoi*) are further constrained by seed availability. Conversely, species with broad agronomic suitability often show limited direct CH₄ abatement. For example, *D. virgatus*, which is suited to regions supporting ~79% of the herd, showed negligible effects on CH₄ emissions, while *S. hamata* also showed little evidence of CH₄ reduction.

General discussion and synthesis

Enteric CH₄ emissions from northern Australian beef systems are structurally high because cattle are typically raised on low-nitrogen tropical forages, experience strong seasonal declines in feed quality, and often have relatively long production cycles before turn-off. Tropical legumes therefore represent one of the few biologically feasible strategies for reducing CH₄ emissions in these extensive grazing systems. Species that combine CH₄ abatement potential (direct and indirect) with broad agronomic suitability and overlap with regions supporting a large proportion of the northern herd represent the most realistic pathways for industry-scale abatement.

This synthesis demonstrated that despite measurable anti-methanogenic effects across several tropical legumes, most of the reduction in emissions intensity arises from improvements in animal productivity rather than direct suppression of methanogenesis. Across production systems, emissions intensity declined by an average of 28%, with ~82% of this reduction attributable to productivity gains. Consequently, species with modest direct effects on CH₄ yield can still deliver substantial abatement if they improve animal performance. *Stylosanthes* spp. illustrate this dynamic; although direct reductions in CH₄ production are limited, its broad adaptation across northern Australia means that widespread adoption could contribute meaningfully to industry-scale abatement through productivity-driven reductions in emissions intensity (Fig. 6). However, these outcomes assume sufficient legume availability to maintain dietary benefits throughout the year. In practice, legume contribution is often highly seasonal and influenced by rainfall, persistence, grazing pressure, and competition with companion grasses, meaning productivity gains – and associated reductions in emissions intensity – are likely to vary substantially across environments, seasons, and years.

Despite clear evidence of productivity and economic gains (e.g. Peck *et al.* 2011; Ash *et al.* 2015; Bowen *et al.* 2018, 2019) adoption of tropical legumes has remained relatively low. For example, *Leucaena* has been successfully established on 125,500 ha in Queensland, which is <2% of the land area of Queensland where it is considered suitable (Beutel *et al.* 2018). Similarly, *S. scabra* and *S. hamata* were estimated to be established on >1 million ha across northern Australia in the late 1990s (Miller *et al.* 1997; Noble *et al.* 2000), which is approximately 3% of the land area considered suitable for these species in Queensland (Peck *et al.* 2022b).

This low adoption reflects persistent agronomic and practical constraints, with many candidate species performing poorly under commercial grazing conditions due to unreliable establishment, limited persistence, seed production constraints, and uncertain profitability (Pengelly *et al.* 2003; Peck *et al.* 2011). Common low-cost approaches, such as broadcasting seed into existing pastures or single-pass cultivation, are widely used but often produce inconsistent outcomes, with frequent establishment failures (Peck *et al.* 2011, 2017). More reliable establishment has been achieved where soil moisture is conserved and competition from existing grasses is reduced; for example, through fallowing prior to sowing and the use of post-emergence herbicides to improve seedling survival (Peck *et al.* 2017). Alternative approaches continue to be explored, such as the use of cultivated legume strip establishment (*Stylosanthes*) in the seasonally dry tropics of north Queensland (Cox *et al.* 2026). Future research should focus on developing and evaluating establishment methods tailored to regional climate and soil conditions, alongside long-term monitoring of persistence and resilience under grazing.

L. leucocephala represents the most agronomically developed and highest-impact tropical legume for northern Australian grazing systems, combining substantial in-animal CH₄ reduction (~22%) with strong productivity gains (Fig. 6). It is best suited to deep, fertile, well-drained soils with annual rainfall typically exceeding 600 mm, where it can contribute 30–50% of the diet for 5–8 months of the year (Dixon and Coates 2008; Charmley *et al.* 2023). Under these conditions, *Leucaena*-based systems can substantially increase LWG and stocking rate. However, wider adoption is constrained by high establishment costs and management intensity, including the need to manage pasture inter-rows, weed control, and grazing to maintain *Leucaena* within browsing height (e.g. Buck *et al.* 2019). Additional limitations include susceptibility of commonly used *Leucaena* cultivars to psyllid infestation, particularly in more humid regions. Biosecurity concerns further restrict expansion in some areas, particularly Western Australia, where *Leucaena* is classified as a high-risk environmental weed due to its prolific seed production (Revell *et al.* 2019).

Other 'frontrunner' species identified in this review include *Desmanthus* spp. and *Stylosanthes* spp. *Desmanthus* spp., particularly *D. virgatus*, are well adapted to the alkaline,

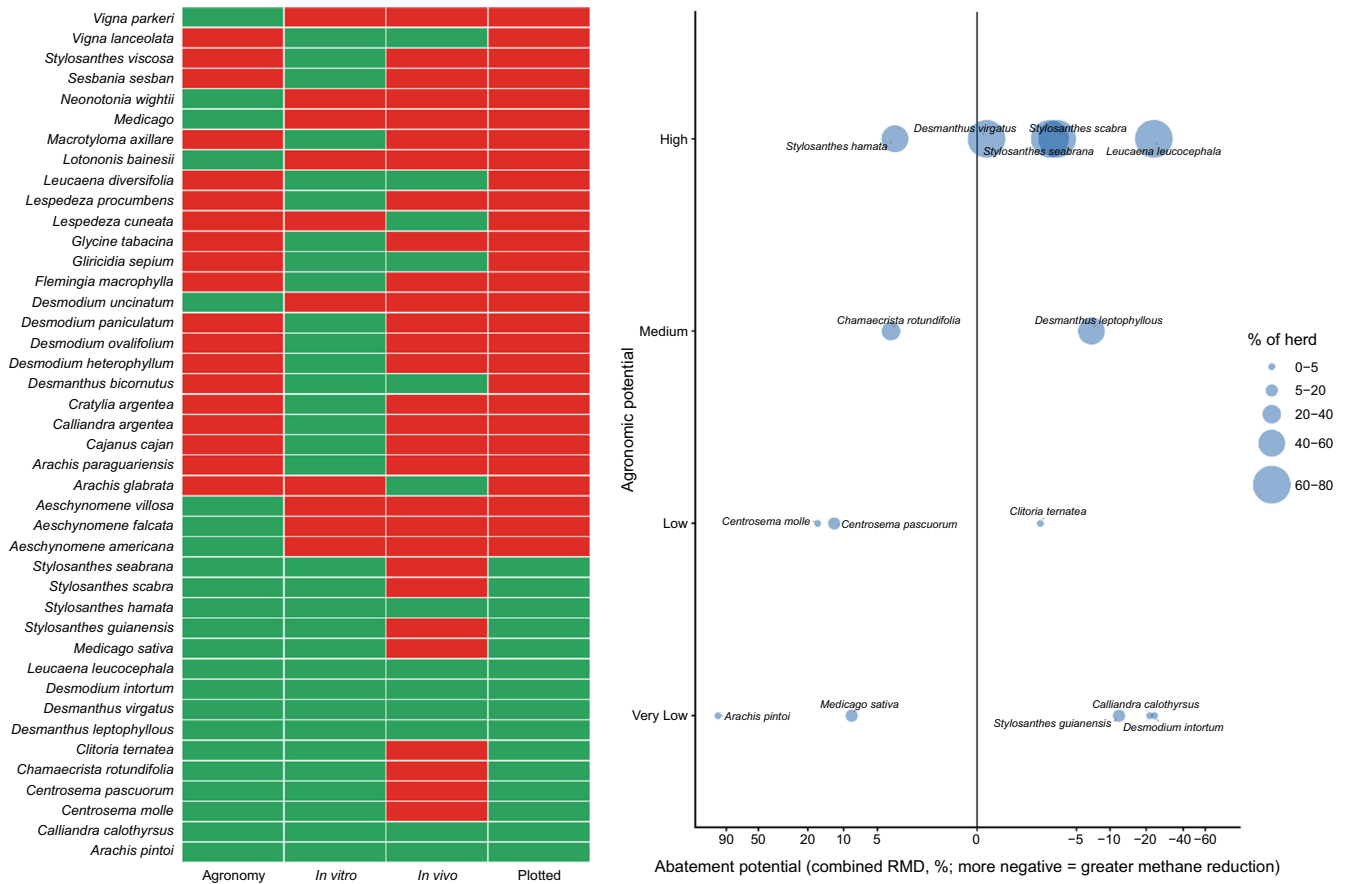


Fig. 6. Integrated assessment of methane abatement potential and agronomic suitability of tropical forage legumes for northern Australian grazing systems. The left panel shows data availability for agronomic suitability and methane measurements (*in vivo* and *in vitro*). The right panel plots methane abatement potential (relative mean difference, RMD; % change in CH₄) against agronomic suitability. RMD values combine *in vivo* and *in vitro* data, with greater weighting given to *in vivo* studies. The x-axis is oriented so that greater methane reductions appear to the right. Bubble size represents the proportion of the northern Australian cattle herd within each species' climatic suitability zone. While RMD captures direct effects on methanogenesis, indirect abatement via productivity is not explicitly quantified but is partially reflected in the agronomic suitability rating, allowing species with strong productivity benefits (e.g. *Stylosanthes* spp.) to be prioritised.

clay-dominated soils. These species tolerate cracking vertosols, seasonal moisture stress, and relatively low fertility, making them suitable for semi-arid environments where other legumes often fail (Gardiner *et al.* 2013; Collins *et al.* 2016). Their compatibility with buffel grass and persistence under grazing are key strengths. However, their performance remains closely tied to soil type, and currently available cultivars have shown variable persistence under commercial conditions, limiting confidence in long-term productivity gains (Peck *et al.* 2022b).

Stylosanthes spp. are among the most widely adapted tropical legumes in northern Australia and are particularly suited to light-textured, well-drained soils of low to moderate fertility. *S. scabra* and *S. hamata* perform well in semi-arid to sub-humid climates, while *S. seabrana* exhibits broader edaphic tolerance. These species are valued for relatively low establishment costs, capacity for self-regeneration, and persistence under grazing. However, establishment success can be variable, particularly where competition from existing grass

swards is high, and productivity responses are generally more modest than for tree legumes such as *Leucaena*. Recent research has focused on improving establishment reliability and evaluating cultivar performance across environments, including frost-tolerant lines that may expand the geographic range of stylos into cooler, frost-prone regions (Peck *et al.* 2026).

It is important to recognise that the success of widely adopted tropical legumes reflects decades of research, development and extension (RD&E) investment, although this effort declined during the 1990s and remains comparatively underfunded, which has slowed the development of new cultivars. In recent years, some new releases have relied on results and trial sites established decades earlier by discontinued pasture evaluation programs, while others originate from international research efforts (Gardiner and Swan 2008). In this context of constrained resources, it is critical that available research funding is directed strategically. Priority should be given to building on existing knowledge and

improving the performance, management, and adoption of proven species with demonstrated agronomic adaptation. Building on existing species is likely to deliver greater and more immediate industry-scale benefits than focusing on novel legumes, while continued exploration remains important to ensure longer-term opportunities are not overlooked.

Adoption of tropical legumes in northern Australian grazing systems is ultimately driven by economic feasibility rather than explicit climate mitigation objectives. Producers are primarily motivated by improvements in animal performance, risk reduction, and enterprise profitability, with increases in LWG and carrying capacity underpinning most observed reductions in emissions intensity. Methane abatement therefore tends to emerge as a co-benefit of improved production efficiency rather than a primary driver of adoption. As a result, the goals of producers and broader policy or industry objectives do not always align: while industry and policy frameworks may prioritise emissions reduction, producers are focused on maintaining profitability and managing risk.

Accordingly, increasing adoption of tropical legumes will require approaches that align CH₄ mitigation with producer priorities and reduce the practical barriers to implementation. This includes reducing establishment risk, improving access to high-quality seed and agronomic guidance, and demonstrating consistent productivity benefits under commercial conditions. Adoption is constrained not only by upfront costs, but also by perceived risk and management complexity, reinforcing the need for systems that are both profitable and operationally feasible. In this context, economic incentives, such as the inclusion of CH₄ reduction from tropical legumes in carbon credit schemes (e.g. development of a method for CH₄ yield reduction from *Leucaena* incorporation), cost-sharing arrangements (e.g. co-investment in establishment), and concessional finance (e.g. low-interest loans), may help reduce financial barriers and support adoption.

Conclusion

Overall, the evidence indicates that tropical legumes have substantial technical potential to reduce the emissions intensity of northern Australian beef production systems. However, there is unlikely to be a single 'silver bullet' species capable of delivering CH₄ abatement across the diverse soils, climates and grazing systems of northern Australia. Instead, meaningful reductions will depend on a portfolio of legumes suited to different environments and management contexts.

This review synthesises the current evidence on the CH₄ mitigation potential of tropical forage legumes in these grazing systems. While some species, particularly *L. leucocephala*, can directly suppress enteric CH₄ production, a substantial proportion of the potential emissions reduction arises indirectly through improvements in animal productivity and shortened production cycles. Consequently, legumes that combine broad

agronomic suitability with measurable productivity benefits may deliver the greatest abatement impact at industry scale.

Realising this potential will require progress across several fronts. Expanding *in vitro* screening and *in vivo* CH₄ measurements will help identify species with stronger anti-methanogenic properties. At the same time, improving establishment reliability, developing a more detailed understanding of regional differences in legume performance, and refining management practices that enhance persistence under grazing will be essential for translating experimental findings into scalable pasture systems. Integrating these advances with spatial suitability analyses and production system modelling will provide greater resolution on where different legumes can make the greatest contribution to reducing emissions intensity in northern Australian beef systems.

Supplementary material

Supplementary material can be accessed from the article page online.

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Data availability. The data that support the findings of this study are available within the article and its Supplementary material. Data derived from previously published studies are cited in the manuscript. Additional data generated from modelling scenarios during this study are available from the corresponding author upon reasonable request.

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Author affiliations

^ASustainable Agroecosystems, School of Biological and Environmental Science, Faculty of Science, Queensland University of Technology, Brisbane, Qld, Australia.

^BQueensland Department of Primary Industries, 203 Tor Street, Toowoomba, Qld 4350, Australia.

^CCSIRO Agriculture and Food, Aitkenvale, Townsville, Qld 4814, Australia.

^DSchool of Agriculture, Food, and Ecosystem Sciences, The University of Melbourne, Parkville, Vic, Australia.