Final report

A Review of anti-methanogenic pastures and forages

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Abstract

The emissions of methane from grazing livestock are of concern to the red meat industry because they are a major source of greenhouse gases (GHGs), may restrict future market access, and negatively affect consumer perceptions of the industry. Some pasture species reduce methane production in the rumen, and they could reduce GHG emissions from the red meat industry. This report reviewed the potential of pasture species to reduce methane from ruminants, evaluated the adoptability of the most promising low methane emissions pasture species, and forecast the likely changes to red meat sector GHG emissions using a simple production and adoption model. A methane avoidance method was also proposed and assessed against field data. Seven prospective species to reduce grazing emissions were chosen: lucerne, brassicas, plantain, *Leucaena, Stylosanthes, Desmanthus,* and biserrula. It was concluded that the opportunity for plant species to reduce methane from grazing livestock was modest due to the generally low reductions in methane these species elicit, and the small contribution they make to the animal's diet. Nevertheless, when adopted across large numbers of livestock they can make a useful contribution towards reducing methane emissions from the grazing sector. Many of the most promising species with anti-methanogenic properties were forecast to improve the nutritive value of pasture, thus increasing reproductive efficiency and animal weight gain leading to changed herd/flock structure, earlier animal turnoff, and increased carrying capacity. Consequently, predicted reductions in methane production per unit of feed intake were often offset by increases in total methane emissions. In summary, the intensity of emissions per unit of animal product is likely to be reduced while total emissions per area may increase. The lack of scientific information on methane dynamics under commercial field conditions hampers the development of a methane avoidance method and further research is required.

Executive summary

Background

Ruminant livestock contribute about 13% of Australia's greenhouse gases mostly as methane. Approximately 90 to 95% of these emissions are from grazing livestock. Therefore, it is paramount that the red meat industry develops methods to reduce methane emissions from grazing animals if the sector is to meet the goals of contributing to Australia's net-zero ambitions by 2050. The review aimed to provide a contemporary update on the key antimethanogenic plants adapted to Australian grazing conditions, quantify the degree of abatement expected under production conditions, assess the likelihood for adoption and to develop concepts for possible methodologies under the Commonwealth Australian Carbon Credit Unit (ACCU) scheme and allied initiatives.

Objectives

The specified project objectives were to:

- Review literature on the technical potential of low emissions plants for inclusion in Australian grazing systems, including agronomic potential, national and regional impact on reducing emissions and identifying research gaps and opportunities.
- Assess the adoptability of low emissions plants in Australian grazing systems, including the stock numbers affected and adoption potential for different pasture applications.
- Assess the potential for methane avoidance programs through voluntary and government programs.

Methodology

- Relevant literature was surveyed to understand the different mechanisms via which pasture biomass reduces methane emissions from the rumen, and which pasture species have shown anti-methanogenic potential via *in vitro* or *in vivo* testing.
- Engagement with researchers, extension personnel, and experts in the field was used to develop a thorough understanding of the practical implications of adopting low emissions species into Australian grazing systems.
- The most prospective species were identified using a simple model that considered methane mitigation, productivity gains, and adoptability. These species were classified as either of national or regional importance and ranked as having high, medium or low impact on methane yield.
- A template for a pastures method for adoption by the Emissions Reduction Advisory Committee was developed and compared against field data.
- A series of recommendations were made and a peer-reviewed paper will be published after acceptance of the report.

Results/key findings

- While there is a large amount of published literature on low emissions forages, understanding the antimethanogenic effects under commercial farm conditions is difficult as most data were collected under laboratory or experimental farm conditions. There is a lack of on-farm data.
- While there is a wide range of plant species that have antimethanogenic activity, only seven forages were considered to have a meaningful influence on methane emissions from grazing animals.
- The reduction in methane yield (g/kg DM intake) from diets with the seven forages varied between 0 and 25%.

- The combined influence of the seven prospective species increased animal productivity by 7% but reduced overall methane emissions by 3% and associated methane intensity (methane per unit of animal product) by 9%.
- The animal performance benefit of the seven species is the main driver for adoption by producers.
- Lower emissions intensity (i.e. emissions per unit of red meat produced) is an important consideration for the Australian red meat sector which exports much product globally.
- The opportunity for developing a method under the Australian Carbon Credit Unit (ACCU) scheme is very low, due to high complexity and low financial returns.
- The opportunity for incorporating low emissions species into grazing systems to increase animal productivity and improve the carbon balance on farm is high, through carbon farming initiatives.
- If performance of livestock on pasture is to be improved, it should be done using regionally adapted low emissions species.

Benefits to industry

The red meat industry is seen as a major contributor to global warming by society and this may be contributing to declining consumption of red meat in Australia as well as a negative sentiment towards livestock producers in general. These facts affect domestic consumption as well as access to international markets where the carbon 'footprint' of foods is affecting sales to lucrative markets. As other sectors reduce their carbon emissions, such as electricity generation, the share attributed to agriculture increases. It behoves the industry to be proactive. Internationally the pledge to cut global methane emissions by 30% over 10 years adds further pressure in the industry to act on enteric emissions (Global Methane Pledge 2025).

Enteric methane is a major source of greenhouse gases, contributing about 75% of all agricultural sources (DCCEEW, 2025). Therefore, the industry should pursue avenues to reduce emissions. With 95% of total methane emissions from pasture, even relatively small reductions from grazing animals can have a major impact when applied at scale across grazing systems. Full carbon accounting in agriculture remains difficult but recent developments, such as in-setting, suggest there will be solutions in the future. While the financial incentive for reducing emissions is unlikely to be significant, the societal benefit is important. Added to this the producer realizes increases in livestock production and financial returns from establishment of higher yielding and higher quality pasture species.

- The review provides realistic, unbiased information on the potential for reducing methane emissions from grazing animals.
- It provides information on the limited options for seeking revenue from avoided emissions through voluntary and government schemes.
- Enteric methane is a major source of greenhouse gases, contributing about 75% of all agricultural sources. Therefore, the industry should pursue avenues to reduce emissions.
- With 95% of total red meat sector methane emitted from pasture-fed animals, even relatively small reductions could have a noticeable impact if applied at scale across grazing systems.
- While the financial incentive for reducing emissions is unlikely to be significant or even possible, the societal benefit is significant.
- Added to this the producer realises increases in livestock production and financial returns from establishment of higher yielding and higher quality pasture species.

Future research and recommendations

- Future research should focus on integrating measurement and estimation of all carbon sources and sinks at the property scale.
- Future research should focus on *in vivo* research with less emphasis on *in vitro* research because it is unlikely that further broad scale screening of species and species growth stage will reveal any prospective new species with the potential for broad impact.
- Research is needed to understand the contribution low emissions forages make to the diet of grazing animals across the year. Methods to estimate or measure the proportion of antimethanogenic species in the diet and how these influence emissions are critical for the national carbon inventory and on-farm carbon accounting.
    - The faecal NIR method needs further validation against laboratory methods and development and expansion of the datasets to produce more reliable estimates of C_3 and C_4 plant species.
    - Development of DNA-based discriminatory techniques are also urgently required as C_3:C_4 ratios are only useful under tropical conditions where grasses are predominantly C_4 species.
- Pasture intake is central to methane production and an accurate and robust method for measuring or estimating intake is essential. Current methods are outdated and need revision or replacement.
- Methane measurement studies using respiration chamber methods (the gold standard) are needed on lucerne, *Desmanthus*, stylos and brassicas to confirm their antimethanogenicity as current datasets are few.
- Methane measurement trials with combinations of low emissions forages as well as low emissions forages with methane mitigating additives are needed.
- Further *in vivo* research on select minor-use tropical legumes including calliandra, lablab and siratro to confirm limited evidence that they may reduce methane emissions

- On-farm long term monitoring to assess seasonal and management effects on methane production of grazing livestock are needed to demonstrate the reduction in methane under commercial conditions. The advent of in-field monitoring units will facilitate this research.
- Extension in promoting the dual benefits of low emissions pasture species on methane reduction and animal productivity should increase adoption rates of the prospective forages nationally. Improving animal productivity from grazing systems is an important industry goal, and widespread adoption of low emissions forages can improve both animal productivity and emissions intensity.

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List of commonly used terms

Term	Description
ACCU	One ACCU is equivalent to 1 tonne carbon dioxide equivalents (CO_2e). The conversion factor for methane to CO_2e is currently 28, meaning it is 28 times more potent at trapping heat in the atmosphere than CO_2.
ACCU method	A methodology developed according to guidelines of the Emissions Reduction Advisory Committee (ERAC) to reduce carbon dioxide emissions in Australia.
Adoption	Describes the uptake of a new method of production or technology in the agricultural sector.
Antimethanogenic	Inhibits or reduces the production of methane in the rumen.
Insetting	The practice of investing in carbon reduction or removal projects within a company's own supply chain or value chain to directly address and mitigate its environmental impact.
Low emissions forage/species	Popular description for an antimethanogenic forage or species.
Methane production	The amount of methane produced by a ruminant measured in g/d or MJ/d, occasionally measured a L/d.
Methane yield	The amount of methane produced per kg feed intake measured as g/ kg dry matter (DM), g/kg organic matter (OM), g/kg digestible DM (DDM), g/kg DOM, MJ/MJ, It can also be given as $ of gross energy (Ym).
Methane intensity	The amount of methane per unit of animal product. Most commonly given as methane per kg LW, carcass weight or saleable meat. The value can account for the lifetime emissions of an animal, but if this is not known then it is expressed relative to a proportion of the lifetime.
Method/methodology	Describes a government-prescribed or voluntary scheme whereby reductions in GHG emissions can generate economic return measured as ACCUs.
Mitigation	A term to denote the reduction in methane production, analogous to antimethanogenic but applies to any greenhouse gas.
NGGI	The National Greenhouse Gas Inventory. Calculated for all greenhouse gases by the Federal government for reporting to the International Panel on Climate Change (IPCC).
Offsetting	Compensating for your own emissions by investing in projects that reduce or remove an equivalent amount of greenhouse gases elsewhere.
Voluntary scheme	The purchase of carbon credits (ACCUs) by an individual or entity to offset their GHG emissions. Voluntary schemes operate separately to the Government ACCU scheme, and are typically less onerous in design.

1. Background

In Australia methane emissions from ruminants represented approximately 13% of total GHG emissions in 2022 (DCCEEW, 2025). Approximately 95% of these emissions are produced by grazing domesticated animals. The Australian red meat sector is under pressure to reduce emissions to meet societal expectations, ensure ongoing market access and to ameliorate climate change. There are currently no viable government schemes to credit producers for reducing emissions from ruminants. Grazing ruminants emit more methane per unit of intake than those raised under intensive grain-based systems. Pasture species contain high amounts of fibre. When digested in the rumen it releases hydrogen that is converted into methane by rumen microbes. Currently, there are few viable options to reduce methane from grazing animals. Additives such as 3-NOP and *Asparagopsis* seaweed can dramatically reduce enteric methane production but feeding additives on pasture is impractical in many circumstances. Novel delivery systems such as in the water supply or slow-release boluses are currently being evaluated but unlikely to reach market in the near term.

Australian grazing systems are diverse and support a wide range of plant species across different agro-ecological zones. Some of these species are known to reduce methane production under experimental conditions, many of these are agronomically suited to inclusion in Australian pastures and are of superior nutritive value to grasses. The extent of reduction in methane of these species has been widely demonstrated *in vitro* (i.e. laboratory testing that mimics animal digestion of biomass) using standardised techniques to measure methane production from a known mass of plant substrate. Results show a wide range in methane production from 8 to 40 mL/g of sample. These promising results have warranted further research studies conducted using ruminants *(in vivo)* where the test plant species is included in a balanced diet at varying proportions and compared against the same diet but without the test species. *In vivo* studies have typically shown smaller anti-methanogenic effects compared to *in* *vitro,* with reductions in methane of between 0 to 25%. Additionally, there is considerable variation between the results of different studies and plant species, in part due to a range of experimental conditions under which the studies are conducted.

There are few on farm studies, so little is known about the mitigation under commercial grazing conditions. Nevertheless, given that grazing livestock (as opposed to grain-fed animals) represent the major portion of the Australian herd, a small reduction in methane across a large proportion of ruminants could still make an important contribution to reducing the GHG emissions from the red meat industry.

Understanding the potential impact of low emissions species in grazing systems requires knowledge of their current penetration into grazing systems and the opportunity for increased adoption, based on economic, climatic and edaphic conditions, and on behavioural characteristics of producers. Characterising the extent of methane reduction under commercial conditions requires an understanding of the mitigation potential of the species, the variation in the contribution of the species to the animal's diet and the associated changes in animal productivity. It is also important to understand the effect of anti-methanogenic pastures on total industry emissions which may increase, in relation to increased animal productivity, or decline in relation to reduced methane per unit of feed intake. The balance between these two conflicting responses is critical to the overall effect of low emissions pasture species on the carbon balance of the industry.

A clear understanding of enteric methane dynamics in commercial farming operations is a prerequisite to reducing the environmental burden of the industry and developing mechanisms whereby producers can benefit from avoided emissions. These may be voluntary, whereby a producer can sell, offset, or inset carbon credits earned into the voluntary market, or government sanctioned schemes, such as in the Australian Carbon Credit Unit (ACCU)

Scheme. The bar for entry into the latter is much higher than for the former, and likely prohibitive in the case of a pastures method.

2. Objectives

In response to the issues discussed, this study aimed to conduct a comprehensive review supplemented by desktop modelling to address the following objectives:

1. Technical

- Review and shortlisting of candidate pasture or forage species/strategies including identification of the mode of action
- Assessment of the rate of reduction in methane emissions achievable on the basis of methane yield (g/kg DMI), methane production (g/d), and methane intensity (g/kg animal production) and accounting for
    - Duration of measured reduction and its relevance in a farming systems context
    - Animal physiological status (e.g. variability of animal response, weaners vs adult stock at maintenance, age)
    - Consistency of reported results across studies, including *in vitro vs in vivo* and in different agroecological zones
    - Impact on emissions within a mixed vs sole dietary component basis
    - Impact of various plant growth stages as emissions reduction potential may vary across the plant life cycle
    - Impact of soil conditions and fertiliser history
- An assessment of the impact on nitrogen intake, utilisation and excretion rate with consideration given to impacts on the net GHG abatement within livestock production systems.
- Consideration of any impacts on animal performance or health

- Identification of research gaps, challenges and opportunities

2. Adoptability:

This component requires an appraisal of the value proposition and likelihood of adoption including consideration of:

- the interaction with animal productivity
- environmental suitability of given strategies (maximum adoption potential in ha)
- establishment cost of new pastures
- risk of failure
- persistence of new cultivars or species in the farming system
- existing levels of adoption of candidate species

Consideration of the relative attractiveness of adoption with and without carbon price signalling.

3. Feasibility as an ACCU method

This section appraises the potential to develop an emissions reduction methodology for the feeding of anti-methanogenic pastures and or forages, including the eventual capacity to audit emissions reduction through the proposed methodology at the farm and supply chain level.

4. Peer reviewed publication

Upon completion of the review, the results will be prepared for submission as a scientific paper to Animal Production Science (or other agreed publisher) for peer review.

3. Methods

3.1 Component one: Technical potential for emissions reduction

3.1.1 Literature review of antimethanogenic candidates

Two critical factors influence the goal to reduce methane emissions from grazing livestock in the red meat sector. Firstly, pasture species need to be identified that reduce the emissions of methane from livestock per unit of dry matter intake, i.e. they reduce the production of methane in the rumen. Secondly these species also must be agronomically suited to significant areas where cattle and sheep are raised, should be productive, persistent and palatable, and should be readily sourced and easily established into grazing systems. The following model describes the factors that affect the impact of any novel grazing system.

Antimethanogenic potential + Agronomic suitability x Number of livestock x Adoption rate

This review will address all four components of this model to identify the opportunity for lower emissions grazing systems in three major agro-ecological zones of Australia where ruminant livestock are important: tropical, temperate and Mediterranean. Broadly these cover northern Australia between 400- and 800-mm rainfall, the mixed farming zone of NSW and Victoria and the mixed farming zones of SE Western Australia, South Australia and parts of NSW, respectively.

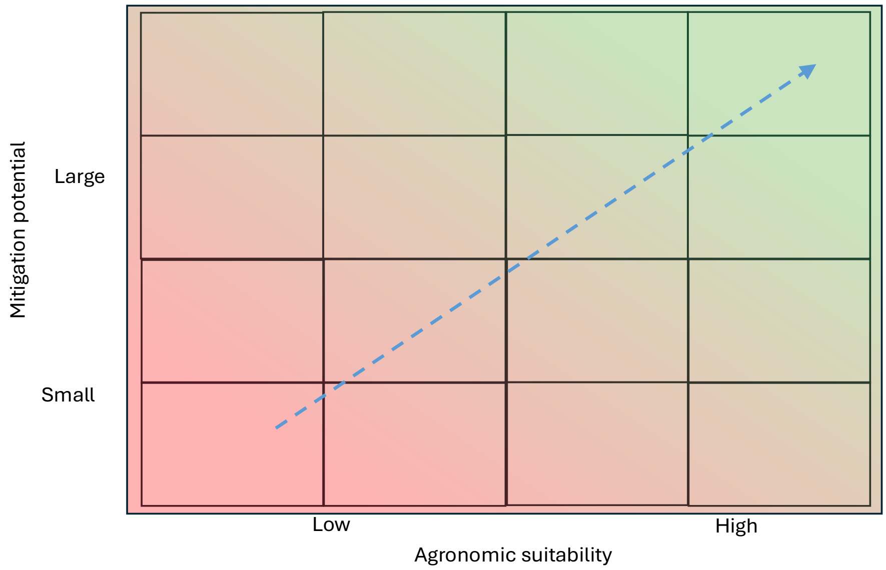
Mode of action will be investigated to understand what mechanism (or combination of mechanisms) is/are important for individual plant species, for example tannins in legumes and saponins in legumes and plantain. This knowledge will be important in selecting complimentary plant species for antimethanogenic pasture mixes.

This review initially developed a ranking of a wide range of species based on their antimethanogenic potential measured *in vitro*. Using the Web of Science search engine, publications from across the World were selected using key words to identify relevant publications. Data was extracted and standardised according to method of methane measurement and measured attributes. Data from individual species were categorised according to species type (temperate legume, temperate grass, tropical legume, tropical grass, brassicas, chicory and plantain).

For *in vitro* datasets, species were ranked according to methane production (mL/g forage substrate). However, for most *in vitro* data, there were no control species against which a measurable reduction in methane can be calculated, so methane concentration was instead evaluated against the mean value for temperate grasses. Species ranked for low methane production were then evaluated to determine species currently of agricultural importance in Australia and to identify possible novel species that may be of agricultural importance.

A similar approach was conducted to evaluate *in vivo* datasets. As the majority of *in vivo* datasets include a comparison with a control species, such as a grass or legume known not to have antimethanogenic potential, it was possible to rank species according to the degree of reduction in methane relative to a control. This was expressed as a percentage in terms of g CH_4/DMI or OMI and g CH_4/digestible DMI or OMI.

Figure 1. Schematic of the scoring approach used in assessing the impact of introducing low emissions species into grazing systems.



Selection of plant species for further consideration was based on their agricultural importance within the three agro-ecological zones in combination with their antimethanogenic potential as stylised in Figure 1. For example, a species with widespread adoption but low antimethanogenic potential may rank as more important than a species with high antimethanogenic potential but of little agronomic potential. This is an iterative process combining the scientific data with local knowledge of production systems and agronomic realities. Occasionally a neglected or novel species may be selected and recommended for further research to determine its possible development as a new species for adoption. The nutritive value and possible anti-nutritive characteristics of the plant species were also included in the selection process. An antimethanogenic plant species with higher nutritive value than the companion forage will increase animal performance and potentially reduce methane emissions per unit of animal product, characterised as methane intensity. A lower methane intensity does not necessarily lower methane emissions if the intake and performance of the animal is increased. Thus, national emissions may increase in response to the introduction of an antimethanogenic species. However, as methane does not recognise national boundaries, a low emissions-intense industry is preferred to a high emissions-intense industry on a global scale.

Screening of *in vitro* data ranked species according to methane production per gram of substrate. Screening of *in vivo* data were according to antimethanogenic potential to reduce methane production scaled for intake (methane yield, g/kg DMI or OMI). Species that reduce animal performance either through antinutritional characteristics or reduced digestibility were removed from further investigation. Species with neutral or positive impact on animal performance were evaluated further. The eventual goal was to select a small number of highly prospective species for each agro-ecological zone, and to identify niche species that may be highly prospective for a small sector of the ruminant industry.

Databases for in vitro and in vivo data have been made available to MLA and a summary is provided in Appendix 2.

3.2 Component two: Adoptability

Adoptability was estimated using the key factors considered to influence adoption i.e., the methane reduction response in terms of production and intensity, the potential for expansion of the area grown, and the typical stocking rates within that area.

3.2.1 Factors influencing adoption

Adoption curves typically follow a sigmoidal pattern with adoption initially slow, then increasing before tailing off as adoption reaches its maximum (Kuehne *et al.* 2017). Figure 2 gives a stylised representation of breaking down a sigmoidal curve into a 'broken stick' model that accounts for Maximum adoption rate (represented by the blue line) and the proportion of time at peak adoption, that is the plateau (red line). Using a novel approach to simplify adoption for the purposes of this review, a linear adoption rate was adopted (the green line) representing the average adoption over 20 years and accounting for the proportion of that time when adoption had plateaued. It is acknowledged that 20 years to peak adoption is arbitrary, for some species it could be longer, for others shorter. However, in the absence of clear data for individual species, a single value was considered the best option to avoid bias.

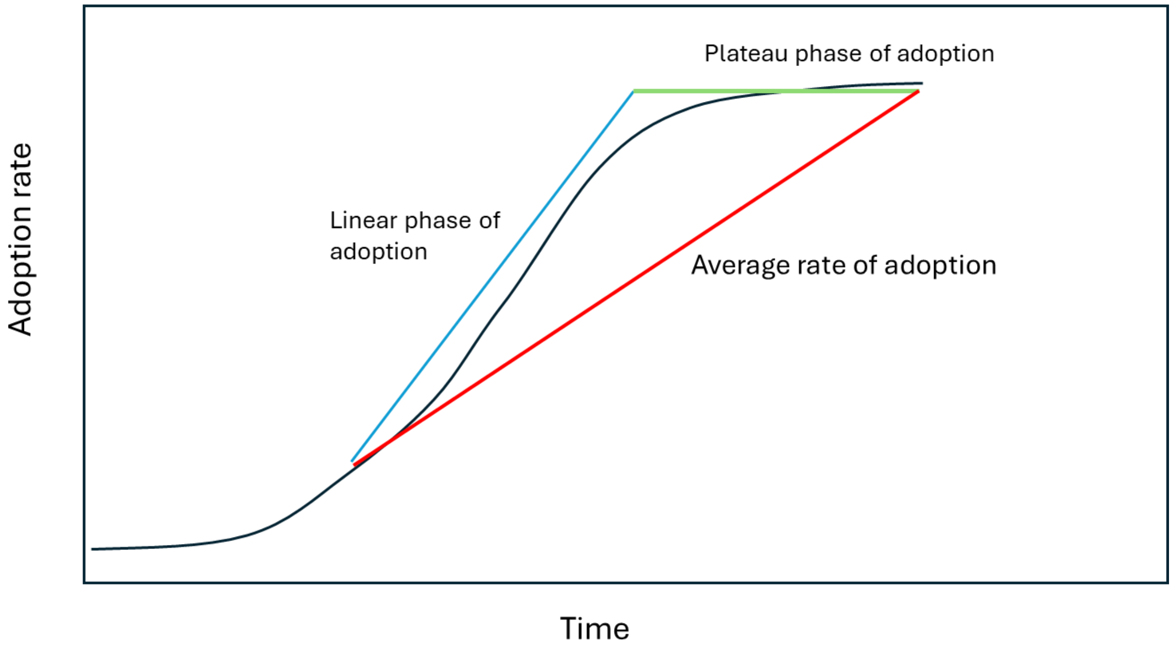


Figure 2. Stylized representation of the adoption model.

Factors that influence adoption are complex. Within the context of low emissions pasture species, it is possible to categorise a number of salient factors including economic, agronomic, environmental, and human behaviour, which broadly reflect the variables used by Kuehne *et al.* (2017) and are described below with commentary of scoring rationale (*in italics*).

Nine categories were designed each with its own weighed score that affected the importance of each category in defining the overall score Table 1. A higher score implied a greater likelihood of adoption. The use of multiple categories allowed for fine tuning of any particular attribute and, if one score was aberrant, its influence on the overall score was minimised. While the method is subjective it allows the relative adoptability of each of the nominated species to be determined. A spreadsheet is available in associated documents. This allows the scoring to be revised in view of improved understanding of these aspects.

Table 1. Adoption metrics used to estimated relative adoptability of selected low emissions forages. The higher the score, the more adoptable a forage.

	Economic		Agronomic		Environmental			Human		
	Cost of adoption	Access to equipment, labour, and capital	Certainty establishment/ persistence	Animal Production	Carbon benefits	Certainty of carbon benefits	Climate stability	Typology	Knowledge and access to information	Mean score
Scale	1 - 3	1 - 3	1 - 3	1 - 5	1 - 3	1 - 3	1 - 3	1 - 10	1 - 10	

Economic

- At the farm level the cost of an adopted practice varies. Adoption of a practice that involved major management change or expenditure was considered differently to a change that requires minimal expense. Change involves a financial cost and this differs among businesses.

  Annual or rotational forages scored lower than perennial forages due to the repeated costs of establishment.

- Access to equipment, labour and capital requires up-front expenditure before any return on the adopted practice can be realised.

  Availability of resources is scarce in the tropical region compared to the broad acre farming systems in the south, thus prompting a lower score in the tropics.

Agronomic

- Establishment and persistence of a species vary according to growing conditions, and this is a salient part of the decision making process around adoption.

Establishment is variable but more so in the pastoral areas of northern Australia than in the cropping areas of southern Australia, thus northern scores tended to be lower than those for the south of the country.

- The yield and feed quality attributes will influence the increased carrying capacity resulting from practice change as will the performance characteristics, turn-off rates and market price of the additional livestock accruing from a practice change. Improvements in individual animal performance coupled with higher stocking rates generally favour a more rapid rate of adoption because the economic benefit is clear.

  Animal production scores were based upon published values for animal performance on prospective forages.

Environmental

- Carbon benefits. A lack of information on the benefits of reducing emissions and no secure revenue stream from avoided emissions reduces the likelihood that carbon benefits will be a major factor in increasing adoption. This is likely to change in the future with the advances in whole farm carbon accounting methods with sequestered carbon and avoided emissions both contributing a lower carbon footprint.

  Carbon benefits are a lesser driver for adoption than productivity, hence the narrow score range. The score reflects the published data for abatement with greater abatement giving higher scores.

- Lack of information on the outcome of a practice change can act as a deterrent to adoption. Lack of scientific certainty in the expected methane reductions and animal response is a deterrent to adoption.

  Low scores were given if data sources were few or showed variability in mitigation. Higher scores were associated with more published data that showed a clear mitigation response.

- Climate variability. The annual and decadal cycles in climate and productivity have been managed and mitigated by a cautious approach both to change and to novel ideas. Relying on past experiences has a major influence on future planning. In the future extreme weather events will become more prevalent and these differ across regions of Australia. Scoring for this category attempts to account for this geographic variation in extreme weather and accounts for drought, excessive rainfall, and extreme temperature.

  High scores were associated with areas of the country less susceptible to climate and weather variability.

Human behaviour

- The typology of the producer determines the likelihood that they will enact a change from business as usual, in this case the adoption of a low emissions forage species. This may be related to their appetite for risk (Webb *et al.* 2013), often linked to their business and financial skills (Holmes 2015). Factors such as their financial circumstances, age, and succession planning will also influence their desire for change. Even in the face of proven benefits, resistance to change is strong, particularly in northern Australia.

  The people aspect of adoption is large and related to their appetite for change, with this being lower (hence lower scores) for those in pastoral versus farming systems.

- Knowledge and opportunity to access information. In contrast to cropping, pasture production is less intensive, requires fewer inputs and does not revolve around an annual cycle of crop production. Consequently, grassland farmers are less exposed to advice from the agricultural supply trade, extension agents and on-line resources. In the absence of information, decision making is challenging and the confidence to try something new is diminished. This is particularly true in northern Australia where the 'tyranny of distance' exacerbates the problem of technology transfer.

  Access to information and level of education differs among regions with generally higher availability of information in the mixed farming zones of southern Australia

While the above methodology enabled the relative adoption of different forages, it did not give a quantitative adoption value, as in percent adoption per year. For three of the prospective species (dual purpose canola, *Leucaena* and *Desmanthus)* adoption rates were known, based on the years since introduction and the current area under production. The mean value of these was then taken as a quantitative measure of adoption of forage species for Australian conditions. The relative aggregated scores for the prospective species were then adjusted to the known mean adoption of brassicas, Leucaena and *Desmanthus* (mean adoption % / adoption score) thus assigning relative maximum rates of adoption to each pasture species. This value was then pro-rated to account for the years at the adoption plateau phase for each prospective forage within a 20 year adoption profile.

3.2.2 Annual mitigation response

The annual response in methane emissions was compared relative to business-as-usual (BAU) before adoption of a low emissions species. The BAU was calculated from the current area and stocking rate (AE/ha) to calculate animal numbers expressed as animal equivalents (AE), where the factor of 8.4 dry sheep units (DSE)/AE was used. The current area for each forage was determined using a combination of data and interviewing extension officers with first-hand knowledge of the forage. Stocking rates within these areas were determined in the same way using available statistical data and information from experts. Using raw statistical data were considered inappropriate when it was impossible to ascertain with certainty the likely proportion of livestock within a statistical region likely to be grazing pastures with low emissions forages.

Dry matter intake for cattle was estimated using the equation of Minson and McDonald (1987). Tables given in the Nutrient Requirements of Domesticated Ruminants (PISC 2007) were use to estimate DM intake of growing and mature sheep. Liveweight gain was assumed to be 0.6 kg/d/AE for all BAU scenarios. Total intake (t/yr) for each forage BAU was calculated as the product of area x stocking rate (AE/ha) x individual annual DMI. A methane yield of 20.7 g/kg DMI was used for BAU modelling (Charmley *et al.* 2016). Methane production was expressed as t methane/yr or t CO_2-e/yr using a factor of 28 (IPCC 2023). Methane intensity was estimated from the total methane (t) over the total AE on an annual basis.

The annual response in methane emissions following adoption was calculated using a similar approach to that described above, with the following complexities. Area was increased according to adoption rates for the seven prospective forages and three minor use forages. Individual animal performance was modified according to data in the literature. Stocking rates (AE/ha) were increased in accordance with the increased animal weights due to higher performance. Methane yield (g/kg DMI) was adjusted based on mean published data for each plant species adjusted to 100% inclusion in the diet. This emission was then corrected for the expected proportion in the diet and the proportion of the year when the species was ingested under commercial grazing conditions. Seasonal variation in the proportion of low emission forages in the diet of grazing livestock is highly variable. Species are seldom present year-round and if present, their contribution to the diet varies widely according to plant species, growing conditions and grazing management. The model uses estimates for the proportion of the year when a species is present and, if present ascribes its proportion in the diet. Data on seasonality was sourced from industry literature and interviews with forage agronomists, while published data on dietary contributions was available for some species including *Leucaena* (Charmley *et al.* 2023a) and *Desmanthus* (Charmley 2025).

The Excel model used to predict BAU and the response to adoption of prospective low emissions species has been made available to MLA and a summary is given in Appendix 3.

3.2.3 Modelling

A farm enterprise-wide model to simulate methane abatement in relation to a range of scenarios was employed. The Crop Livestock Enterprise Model (CLEM; Crop Livestock Enterprise Model (CLEM) – LiveGAPS) is currently being revised with updates to bring the model consistent with the latest biological understanding of energy and protein dynamics in ruminants (MLA 2023). The author wishes to point out that the data generated is from a pre-release of the CLEM update. CLEM is a whole-of-farm enterprise model that can test a range of farm improvement strategies in a multitude of crop and livestock systems while tracking impacts on finances, natural resources, and highly constrained resources such as labour. Three low emissions forages were chosen based on characteristics that encompassed the range in abatement possibilities. Brassicas for a mixed farming zone in New South Wales were chosen due to their presumed high abatement potential and their high inclusion rate in the diet. *Desmanthus* was chosen to represent a more extensive grazing system in central Queensland because of its low mitigation potential and its highly variable inclusion rate in the diet of grazing animals (Table 2). Finally, a central Queensland breeder herd scenario was examined with either *Leucaena* made available to breeders and growers to demonstrate the impact on herd structure, or *Leucaena* only available to growing cattle (a more typical commercial scenario). Unfortunately, CLEM modelling was unable to fully capture the herd dynamics, so a simple excel modelling approach was used.

Brassicas scenario

The model was based on feeding forage brassicas to growing Angus steers in the high rainfall zone of New South Wales. Mortality was fixed at 0.125% per month. The baseline feeding system was winter grazing of a Phalaris/subterranean clover sward. Cattle were introduced to brassicas gradually in March reaching a 90% inclusion in the diet after 14 days and were held at this inclusion level for 131 days. Two mitigation levels were compared, low and high. Low mitigation was modelled at a methane yield 5% less than baseline, while the high mitigation level was 20% below baseline. These values were chosen as representative for the extremes of published data

Desmanthus scenario

A buffel grass pasture on a central Queensland property was chosen to model the effect of including *Desmanthus* on animal productivity and methane emissions. Female tropical composite cattle were introduced at 250 kg in January and grazed for 12 months. Mitigation was set at a 21.7% reduction in methane yield assuming a100% *Desmanthus* diet. Two levels of overall mitigation were achieved by changing the proportion of *Desmanthus* in the diet on a monthly basis (Table 2).

Table 2. Inclusion levels of *Desmanthus* by month used in the CLEM modelling.

Inclusion (% diet)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Low	20	20	20	20	15	10	5	5	5	5	5	10
High	40	40	40	30	25	20	10	10	10	10	15	25

Leucaena scenario

For the final evaluation a tropical 130 head composite breeder herd in central Queensland was chosen to model the impact of including *Leucaena* in the diet of lactating cows and growing cattle from weaning to a sale age of 600d. The mitigation effect was calculated at 9% after accounting for the proportion of *Leucaena* in the diet (30% inclusion and the grazing season for Leucaena of 7 months a year. The baseline diet was typical *Bothriochloa petusa* dominated mixed sward with minimal legume content. The simulation covered 12 months beginning in January after calving was completed. Weaning rates were taken from Cashcow (McGowan 2014) and varied between 77 and 88% depending on parity. Mortality varied fem 4 to 10% up to the 6th parity, thereafter it increased from 18 to 27% such that no cows remained in the herd for more than eight parities. The effect of including *Leucaena* was modelled with *Leucaena* available to the whole herd (breeders and growing cattle) or only to growing cattle.

3.3 Component three: Feasibility as an ACCU method

Since the establishment of a Commonwealth scheme to reduce enteric emissions in the red meat industry only two methods have been approved, both of which have been discontinued as neither method attracted widespread interest from the red meat industry. A recent proposal to the Emissions Reduction Assurance Committee (ERAC) for a supplements and forages method was not approved in its current form on the grounds that further work and supporting evidence was needed. The conundrum is that for compliance with the requirements of the ACCU scheme, verifiable abatement methodologies are difficult to develop for ruminant production systems and therefore complex and expensive to adopt by industry. A complex, verifiable method will not be adopted by the industry. However, a simple low-cost method will not be approved by ERAC.

The approach here was to showcase a method that must be;

- Applicable to a large sector of the red meat industry
- Readily aggregated across multiple producers
- Simple and cost effective to adopt
- Rigorous enough to meet the requirements of the ACCU scheme

3.3.1 Development of a potential ACCU scheme method

A proposed methodology for Leucaena was developed by Gordon and Wiedemann (2023), and a similar approach was taken here for application across a wider range of pasture species. The method relies upon establishing a baseline year, which in this case is the emissions from business as usual, that is methane emissions from grazing cattle on pasture without low emissions species. In this scenario the area, numbers, classes and performance of livestock are taken into account. Commercially several carbon farming consultants have the necessary skills and models to simplify the approach for producers. Meat and Livestock Australia also have carbon accounting models for dairy (D-GAF) and beef and sheep (SB-GAF) producers.

Any method should be compatible with the National Greenhouse Gas Initiative (NGGI) and should use the same metrics for estimating methane from dry matter intake. The proposed method described in Section 4.3.1. used values for the reduction in methane yield developed in section 4.1 and also accounts for any changes in animal performance. To achieve a net reduction in methane, the abatement per animal must be greater than emissions from the additional animals grazing within the defined method area on the property.

3.3.2 Testing the method

Through the Methane Emissions Reduction in Livestock (MERiL) program, Agrimix Pastures® secured funding to measure the response in methane emissions from cattle grazing pastures with and without inclusion of a low emissions pasture species, in this case *Desmanthus*. The research was contracted to CSIRO and Agrimix have agreed to allow the use of these data in this review. Results for the methane data collected in the field using gas emission monitoring (GEM) units were compared with those estimated by the proposed method. The research has been submitted to Animal Production Science (Charmley *et al.* submitted).

The 16-month field study of cattle grazing non antimethanogenic and antimethanogenic pastures in a replicated on-farm trial was conducted in central Queensland. All paddocks were located in the same area on cracking clay soils. The control treatment was >90% buffelgrass while the treatment was buffel grass with between 20 and 40% *Desmanthus* in the pasture in the wet season. Methane production was measured throughout the study using GEM units

Figure 3. Gas emissions monitoring (GEM) unit deployed for long-term monitoring of methane from grazing cattle.

Animal weight, pasture composition and diet quality were measured periodically throughout the study. The reduction in methane production, yield and intensity was calculated from the field data (observed data). The reduction in methane yield was also estimated using the proposed methodology. Dry matter intake was calculated using the equation of Minson and McDonald (1987) calculated from LW and LW change. The proportion of *Desmanthus* in the diet was estimated from difference in non-grass species in control and treatment paddocks.

4 Results

4.1 Component one: Literature review of technical potential for emissions reduction

4.1.1 The role of the rumen

The rumen maintains a complex microbial ecosystem under anaerobic conditions. An active and balanced rumen microbiome is essential for ruminants allowing them to derive energy from complex carbohydrates, including cellulosic plant fibres. This microbiome comprises bacteria, archaea and protozoa which have specific roles in relation to the production of methane. Bacteria are primarily responsible for the anaerobic fermentation of dietary carbohydrates to volatile fatty acids, principally acetate, propionate and butyrate. In so doing hydrogen (H_2) is produced, with the amounts being determined by the molar proportions of acetate (more H_2) and propionate (less H_2). High concentrations of H_2 in the rumen can inhibit microbial activity (Morgavi *et al.* 2010). The archaea, a primitive group of single-celled organisms like, but distinct from bacteria, play a central role in controlling H_2 in the rumen through reaction with a carbon source (CO_2) to produce methane (methanogenesis). While CO_2 is the principal substrate for methanogenesis in the rumen, methyl compounds and acetate can also act as substrate for methanogenesis by the archaea (Beauchemin *et al.* 2020). Smaller proportions of hydrogen can also be directed into propionate, acetate, hydrogen sulphide and ammonia (Beauchemin *et al.* 2008).

4.1.1.1 Mode of action

Broadly, there are two mechanisms whereby pasture species can reduce methane production in the rumen: one through a direct effect on the rumen microbiome through interference with methanogenic pathways and the other through a range of dietary influences on chemical composition of the diet, rumen fermentation, intake and rate of passage of nutrients from the rumen. The former mechanism reduces methane per unit of intake (yield), while the latter may still influence methane yield, it often has a greater impact on the amount of methane produced per unit of output (methane intensity as g methane per kg liveweight, carcase weight, milk or wool). Under commercial production scenarios, an intervention may have contradictory effects on yield and intensity, such that production, either as per animal or per hectare may increase, thus affecting national inventory, while methane yield and/or intensity will decline. Many forage species in grazing systems affect both modes of action, resulting in complex outcomes especially at the property level.

4.1.1.2 Nitrous oxide emissions

Nitrogen in the diet contributes to GHG emissions though the release of nitrous oxide (N_2O) from urine and faeces. In simple terms, as the N content of the diet increases the ability of the rumen to capture ammonia (the breakdown product of rumen degradable protein (RDP)) is reduced. Ammonia leakage to the blood stream results in increased urea excretion in urine that can contribute to N_2O emissions. While most forage diets are low in N, there are some exceptions as well as specific conditions in the rumen which can reduce N digestion in the rumen. Crude protein in forages is highly soluble and rapidly breaks down to non-protein N (NPN) in the rumen. This can lead to an asynchrony between available energy and NPN leading to inefficient microbial protein synthesis. Bowen *et al.* (2017) conducted grazing studies with pastures ranging in CP from 2 to 35%. The efficiency of microbial synthesis per unit of digestible OM intake (DOMI) increased almost 10-fold as the ratio of RDP to DOMI increased. They observed that at a dietary CP of approximately 15 to 20% DM there was a plateau in efficiency of microbial protein synthesis leading to marked increases in rumen ammonia in excess of 200 mg/L. While pasture legumes are often in excess of 20% CP, they seldom account for over 50% of the diet. However, excessive losses of urea in the urine are possible under certain circumstances. In a review by Gerber *et al.* (2013) matching the CP content of the diet to the animal's requirement was considered to be the best nutritional option to reduce N_2O emissions. Charmley *et al.* (2023a) observed rumen ammonia N levels to range from 53 to 194 mg/L in grazing cattle as the percent non-grass in the diet (mostly *Leucaena*) increased from 30 to 40% and diet CP from 9 to 15% DM. As these levels were approaching 200 mg/L, the possibility of increased N_2O emissions from grazed pastures cannot be discounted. Similar situations are likely to arise, such as sheep grazing ryegrass/biserrula pastures in WA where the diet CP can be double the requirements of dry ewes.

Many of the low-emissions legumes contain tannins that can reduce the solubility of CP by complexing with proteins rendering them less available for catabolism to peptides, amino acids, and ultimately, ammonia in the rumen and urea in the urine (Carulla *et al.* 2005; Archimede *et al.* 2016). This may go some way to offsetting the effect of high CP legumes like *Leucaena* contributing to elevated N_2O emissions. Suybeng *et al.* (2021) observed higher faecal N in cattle given *Desmanthus* compared to lucerne, suggesting that the effect of tannins in the *Desmanthus* was reducing the solubility of CP in the diet, leading to higher excretion in faeces and potentially lower urine N. As the solubility of N in faeces is lower than that in urine this may further contribute to offsetting the effects of higher CP diets containing legumes.

Annual nitrous oxide emissions from pastures range from 0.2 kg N/ha in extensive rangelands (Dalal *et al.* 2003) to 11 kg N/ha under intensive temperate grasslands (Murphy *et al.* 2022) and are derived from fertilizer N, N release from pasture soil disturbance, and N from faeces and urine (Dalal *et al.* 2003). In unfertilized pastures without legumes, urine contributes approximately 75% of the N_2O with the remainder derived from faecal N. Legumes can release approximately 75 to 150 kg nitrate-N/ha from atmospheric N fixed by symbiotic *rhizobia* (Dalal *et al.* 2003) and thus contribute to N_2O emissions. Luo *et al.* (2018) measured N_2O following the application of urine to ryegrass, clover, lucerne and plantain swards. In the absence of urine, emissions were higher for clover swards (0.93 kg N_2O -N/ha) compared to the other species (~0.1 kg N_2O -N/ha), due to N fixation in the clover. Application of urine at an equivalent rate of 622 kg N/ha increased N_2O emissions in all swards, but the effect was least for the plantain sward. The results demonstrated that legume swards contribute N to the soil due to N fixation (which is cyclical) but are likely to increase N_2O emissions. Different swards can exhibit different N_2O response due to urine patches. The importance of this will be determined by the stocking rates and climatic conditions (Dalal *et al.* 2003).

It is concluded that while pasture legumes can have high concentrations of CP, the fact that legumes seldom account for more than 50% of the diet and also contain tannins, goes some way to reducing their contribution to N_2O emissions from the animal.

4.1.2 Plant bio-actives to reduce methanogenesis in the rumen

There are many good reviews on the factors that reduce the amount of methane produced in the rumen of grazing ruminants (Beauchemin *et al*. 2008; Aboagye and Beauchemin 2019; Beauchemin *et al*. 2020; Ku-Vera *et al*. 2020; Rufino-Moya *et al*. 2021; Ungerfeld and Pitta 2024). The most widely known bio-actives will be discussed here.

Tannins

The predominant bioactive in the many legume species that inhibit methanogenesis are a group of compounds generally referred to as tannins (Aboagye and Beauchemin 2019). Tannins are a group of polyphenolic compounds found in plants often acting as defence against attack by insects and other plant predators. Condensed tannins (CT) are high molecular weight (MW) compounds often associated with reducing the solubility and availability of proteins and to some extent fibre in the digestive tract, as well as reducing digestibility. More recently their role in reducing methanogenesis has received much attention. In temperate legumes condensed tannin concentration can vary widely (0 to 10%) between species and within a species across growth stage (Jayanegara *et al*. 2012). Condensed tannin concentration is typically higher in tropical legumes (up to 24% DM) and hydrolysable tannins (HT) are also found in tropical legumes in amounts varying between 7 to 14% DM (Aboagye and Beauchemin 2019).

The role of tannins in reducing methanogenesis is poorly understood, as is the effect of CT versus HT, particularly in tropical legumes. Jayanegara *et al.* (2012) conducted a meta-analysis of both *in vitro* and *in vivo* experiments and showed that as tannin concentration increased in the diet, methane production was reduced, although the authors were unable to differentiate between type (CT *versus* HT) or MW of tannins studied. They also noted that for *in vitro* experiments, the response was curvilinear with no further reduction in methane production when the tannin concentration was above 10%. However, for *in vivo* trials, the response was linear up to a tannin content of 20% DM. This casts doubt on the usefulness of *in vitro* experiments as predictors of the response *in vivo*.

More recently (Martins *et al.* 2023) conducted a meta-analysis on a large dataset of *in vitro* studies of which there were 328 observations on the effect of tannins on methane production. They observed a 17.5% reduction in methane production, with no effect on digestibility or total VFA production. Orzuna-Orzuna *et al.* (2021) analysed 32 *in vivo* publications where tannins were included in the diet of beef cattle. They concluded that tannins did not influence weight gain, feed efficiency or N use efficiency but did reduce methane yield by 6% from a mean tannin content of 1.46% DM. The analysis did not allow for a dose-response effect to be tested. The difference in the magnitude of the mean difference between *in vitro* and *in vivo* studies (17.5% versus 6%) demonstrates the danger of extrapolating from laboratory to the animal. However, the lack of effect of tannins on *in vivo* digestibility and animal growth performance from such large datasets is encouraging. It should also be noted that these meta-analyses were not restricted to tannins in plants but also included tannin extracts.

The mode of action by which tannins reduce methane emissions is complex, and different mechanisms appear to be at play depending upon the nature of the tannins, and the companion feeds and nutritive value of the diet (Archimede *et al.* 2016; Aboagye and Beauchemin 2019; Berca *et al.* 2023). Condensed tannins can reduce the activity of methanogens either directly or indirectly through a depressive effect on protozoa (Archimede *et al.* 2016). They have also been implicated in altering the acetate:propionate ratio in the rumen as a result of depressed fibre digestion (Tiemann *et al.* 2008a; Berca *et al.* 2023) which reduces H production and hence methane formation. Elucidating a dose response to CT is difficult as not all CT act with the same antimethanogenic activity. Generally, it is believed that higher MW tannins exert a greater antimethanogenic effect than lower MW CT (Saminathan *et al.* 2015; Mueller-Harvey *et al.* 2019). Recently, hydrolysable tannins (HT) have been implicated in reducing methanogenesis in the rumen (Aboagye and Beauchemin 2019). Stewart (2018) demonstrated a greater reduction (39%) in methane yield in heifers fed hays from HT containing species compared to those containing CTs. Aboagye *et al.* (2019) showed a 9 % reduction in methane yield when gallic acid, a principal component of HT was added to lucerne silage fed to growing heifers. A direct toxic effect of HT on protozoa has been implicated as the cause for reduced methanogenesis (Aboagye and Beauchemin 2019).

Saponins

Saponins are found in a range of plant species capable of persisting in Australian grazing systems (Badgery *et al.* 2023). They have a direct toxic effect on the rumen protozoa (Kholif 2023), and as approximately 20 to 30 % of methane is thought to be derived from methanogens associated with protozoa in the rumen, a related reduction in methanogenesis is often observed (Guo *et al.* 2008; Holtshausen *et al.* 2009). *In vitro* studies revealed a reduction in methanogenesis when combinations of tannins and saponins were evaluated and suggested an additive effect of the two bioactive compounds (Jayanegara *et al.* 2020). *In vivo* studies by Sliwinski *et al.* (2002) did not find a reduction in methane yield when saponin extract from *Yucca schidigera* were fed to lambs at up to 30 mg/kg DM. However, Molina-Botero *et al.* (2019) observed an approximate 10% reduction in methane yield when foliage of *Gliricidia sepium* and pods of *Enterolobium cyclocarpum* were added to cattle fed *Brachiaria* forage. However as both tannins and saponins were present it was impossible to ascribe the reduction to saponins specifically. Ruminants can adapt to saponins in the diet, thus the permanence of reduced methanogenesis can be an issue (Kholif 2023), although Ramirez-Restrepo *et al.* (2016) observed persisting reduction in methane production several weeks after supplementation with tea seed saponins had ceased and Molina-Botero *et al.* (2019) noted sustained reduction in methane yield over 80 days. While saponins influence methanogenesis, the data is equivocal and further research on the role of saponins is warranted.

Glucosinolates

Forage brassicas, including kale (*Brassica oleracea*), turnip (*Brassica campestris*), forage rape (Brassica napus), and swede (*Brassica napus ssp. rapifera*) contain glucosinolates (Sun *et al.* 2015). Brassicas have been shown to reduce methane emissions in sheep (Sun *et al.* 2012b; Sun *et al.* 2015) but the evidence for reductions in methane when cattle are fed brassicas is less clear. Williams *et al.* (2016) observed only a small non-significant reduction in methane yield when fed to dairy cows at 60% of the diet. The mode of action is unclear but a range of glucosinolates, nitrate and sulphate have all been implicated. Sun *et al.* (2015) noted changes in the rumen microflora favouring propionate over acetate that would reduce H production in the rumen. In a subsequent review, Sun (2020) speculated that breakdown products of glucosinolates may release thyroid hormone that in turn increased digesta turnover in the rumen thus reducing methane emissions, however this has been refuted (Todini and Fantuz 2023). Leanne Dillard *et al.* (2018) investigated the influence of forage brassicas on methane production in continuous culture. They observed marked reductions in methane per gram of organic matter incubated for canola and rapeseed (80% reduction) and an even greater reduction for turnip (90%) but were unable to identify causative agents responsible for these reductions. Stepwise multiple regression revealed that neutral detergent fibre accounted for over 70% of the variation in methane, but no relationship was seen for acetate:propionate (A:P) ratio, even though this has been implicated in reducing methane by others (Janssen 2010). Although correlation analysis between individual and total glucosinolates showed significant negative relationships with methane production, the authors (Leanne Dillard *et al.* 2018) did not ascribe causality.

Nitrates

The antimethanogenic potential of nitrates is well documented (Callaghan *et al.* 2014; Nolan *et al.* 2016; Tomkins *et al.* 2018) and a nitrates methodology was approved by the Australian government as a potential supplement to replace urea for the extensive cattle industry in northern Australia (Commonwealth of Australia, 2014). However, due to the risk of nitrite poisoning following reduction of nitrate in the rumen (Benu *et al.* 2021) inclusion levels of nitrate were too low to elicit a significant reduction in methane (Tomkins *et al.* 2018). The methodology has subsequently been withdrawn without any industry uptake. Nevertheless, nitrates can be found in forage, particularly after the application of nitrogenous fertilizers and has been shown to reduce methane from ryegrass diets (Warner *et al.* 2016).

Nitrate and sulphate are found in high concentrations in many brassicas and can reduce methane production by acting as electron acceptors in the rumen (Nguyen *et al.* 2016). Sun *et al.* (2015) were unable to find a clear relationship between the concentration of nitrates and sulphates in the diet of brassica-fed sheep and concluded that their role was minimal in the overall antimethanogenic impact of brassicas. It is inconceivable that such large reductions in methane in livestock fed brassicas cannot be ascribed to any single effect in the rumen environment. Changes in acetate:propionate ratio or presence of nitrates in and of themselves are unlikely to reduce methane by in some cases, over 50%. Further research is needed in this area to identify causation and confirm the methane reductions following feeding of brassicas as observed by Sun *et al.* (2015).

4.1.3 Rumen fermentation patterns in high and low quality forages

When very high-quality grasses (DMD >70%) such as perennial ryegrass, are included in ruminant diets methane production and yield is often lower than for diets not including very high-quality grasses. Several reasons for this effect have been proposed. Reduced methanogenesis has been attributed to a lower A:P ratio in the rumen (Purcell *et al.* 2012) as a consequence of a high concentration of fermentable carbohydrate in the diet. High water soluble carbohydrate (WSC) ryegrasses cultivars have been developed but their antimethanogenic potential has been disappointing. Staerfl *et al.* (2012) did not find a reduction in methane production or yield when comparing a high WSC variety with a conventional ryegrass variety. Similarly, Jonker *et al.* (2018) observed only a small and highly variable response in methane yield of sheep. A possible explanation for this may have been related to the lower N content of the high WSC cultivars. High levels of N can lower methanogenesis simply by substituting carbohydrate in the diet. Woodmartin *et al.* (2024) compared several diets for sheep with contrasting N intake ranging from 29 to 41 g/d. N intake accounted for 84% of the variation in methane yield. In addition, highly digestible diets can lower pH in the rumen that inhibits the activity of protozoa and methanogens (O'Neill *et al.* 2011; Sun *et al.* 2015; Woodmartin *et al.* 2024). The use of inorganic N fertilizer can result in high levels of nitrate in grasses, particularly ryegrasses and brassicas. Nitrate can act as a H sink in the rumen reducing H available for methanogenesis (Nguyen *et al.* 2016). Navarro-Villa *et al.* (2011) using *in vitro* techniques observed a significant correlation between nitrate and methane production when the nitrate content of ryegrass ranged from 1.15 to 2.3 g/kg DM.

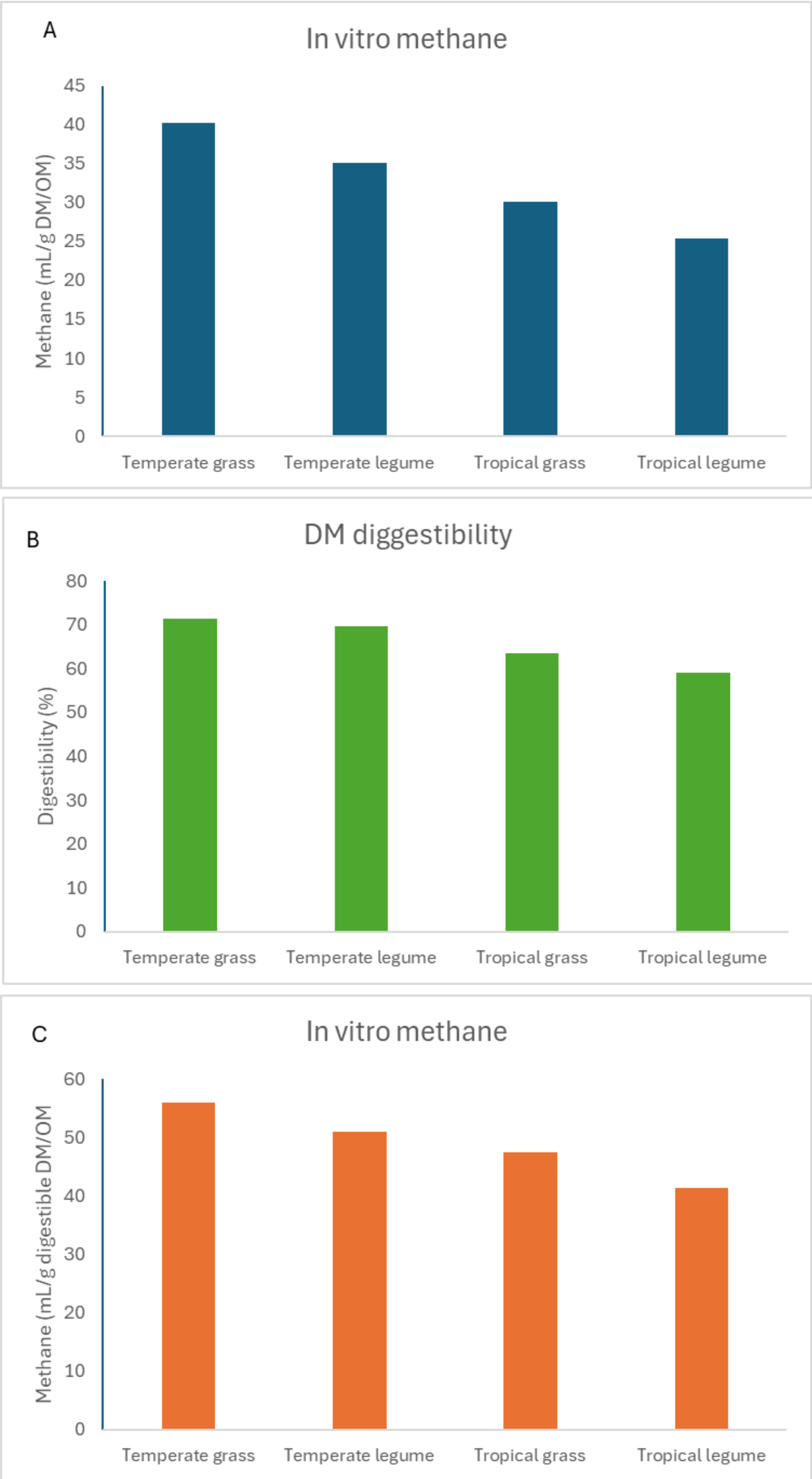
While highly digestible forages are unlikely to be found under most Australian conditions, the complex interactions observed in these diets between carbohydrate and N fractions and N solubilities demonstrates the importance of accounting for all possible factors that can influence the production of hydrogen in the rumen. Under certain conditions pasture species can be high in nitrate, and nitrate was proposed as an antimethanogenic additive for northern beef cattle.

Very low-quality forages, such as may be encountered in the dry season in northern Australia may, conversely, have the opposite effect on methane emissions through a combination of higher acetate:propionate ratio and high retention time in the rumen (Goopy *et al.* 2020). Kennedy and Charmley (2012) fed low quality tropical grasses ranging in OM digestibility of between 47 and 62%. Organic matter intake increased from 1 to 2% LW. However, the acetate + butyrate:propionate ratio decreased, rather than increased from 5.8 to 5.0 but methane yield was still decreased from 22.4 to 18.9 g/kg DMI. There was no evidence that low-intake, low quality grasses produced higher methane than better quality forages. Conversely, (Goopy *et al.* 2020) found increased methane yield from 29 to 31 g/kg DMI as feed intake was reduced from maintenance to 0.4 maintenance. However, this was achieved by feed restriction not a reduction in feed quality. Muetzel et al (2024) following a meta-analysis of New Zealand cattle data showed a higher methane yield at lower feed intakes. This contrasts with Australian data where feeding level had no effect on methane yield (Charmley *et al.* 2016). It is concluded that there is insufficient evidence to indicate that methane yield may be increased on very poor dry season pastures characterised by low voluntary intake, but further research is needed to confirm this.

4.1.4 Low methane pasture species – *in vitro* studies

There are many plant species that have been shown to reduce methane emissions *in vitro* and *in vivo*, although the magnitude of reduction is typically less *in vivo* that in the laboratory. A list of references of *in vitro* studies used in this review is given in Appendix 8.1. These species vary according to geography and will be discussed in relation to three agro-climatic zones; tropical, temperate and mediterranean. Grasses and legumes comprise the majority of pasture species and these can be classified into temperate and tropical species. Typically tropical grasses and legumes exhibit lower methane production compared to temperate species when incubated *in vitro (*28 *versus* 38 mL/g DM/OM). However, as tropical species are less digestible than temperate species (61% versus 71%), methane emissions per unit of digestible material are closer than when expressed on a total substrate basis (Figure 4).

Figure 4. ***In vitro*** **methane expressed as mL/g DM (A) or digestible DM (C), and digestibility (B) for temperate and tropical grasses and legumes. See Appendix 8.1 for references**



4.1.4.1 Tropical pasture species

Most tropical species that reduce methanogenesis in northern Australia (defined as north of the Tropic of Capricorn) are members of the *Leguminosae* family. Typically, the primary bio-actives in forage legumes are tannins and the extent of reduction in methanogenesis is broadly related to the concentration and chemical nature of the tannins. Legumes as distinct from grasses are generally higher in N content and lower in digestibility, but at any given digestibility exhibit higher voluntary intake due to the higher proportion of hemicellulose in the fibre fraction (Castro-Montoya and Dickhoefer 2020).

A wide range of tropical forage legumes have been tested *in vitro* to determine their antimethanogenic potential (Durmic *et al.* 2016; Vandermeulen *et al.* 2018; Singh *et al.* 2023). *In vitro* data typically report the amount of substrate added, total gas production (a measure of digestible substrate) and methane production. Methane can then be expressed relative to both the amount of substrate and to the amount of gas produced. The latter is an important consideration as some legumes restrict the total microbial activity, so a low methane yield can be simply due to a low overall level of fermentation. The majority of data are derived from batch culture studies following fermentation over a fixed time in a closed system (Durmic *et al.* 2017). Somewhat fewer studies employ steady state fermentation over extended periods for example using the rusitec system (Hess *et al.* 2008). The two systems are not directly comparable (Kelln *et al.* 2023). As distinct from *in vivo* trials, *in vitro* studies typically measure methanogenesis from 100% inclusion of the “diet”, often resulting in greater reductions in methane than seen *in vivo* systems where the test species is fed as a component of the diet. While some *in vitro* trials compare antimethanogenic species with a non antimethanogenic species such as a grass, others do not. For those that do include a control, the extent of change in methanogenesis is highly dependent upon the microbial and methanogenic activity of the control species. This makes comparison across or even within studies difficult. If methane production from tropical grasses (30 mL/g) is considered a threshold below which a methane reduction effect is indicated, then many tropical legume species are below this value.

A summary of the *in vitro* literature on tropical legumes is included in Table 3 and Figure 5. Eighteen publications were included in the review representing a total of 546 observations and 28 different species. A list of cited references contributing to Table 3 is given in Appendix 8.1. For a number of these species, they were represented by very few datasets and were for genera or species of little agronomic significance for Australia (*Atylosia*, *Cajanus cajan, Calliandra, Flemmingia, Gliricida, Lespedesia*). *Calliandra* was represented by two species, one of which markedly reduced methane production *in vivo* while the other did not when measured in continuous culture (*in vitro*). A species similar in growth habit to *Leucaena,* its agronomic suitability to higher rainfall areas of Australia may warrant further investigation.

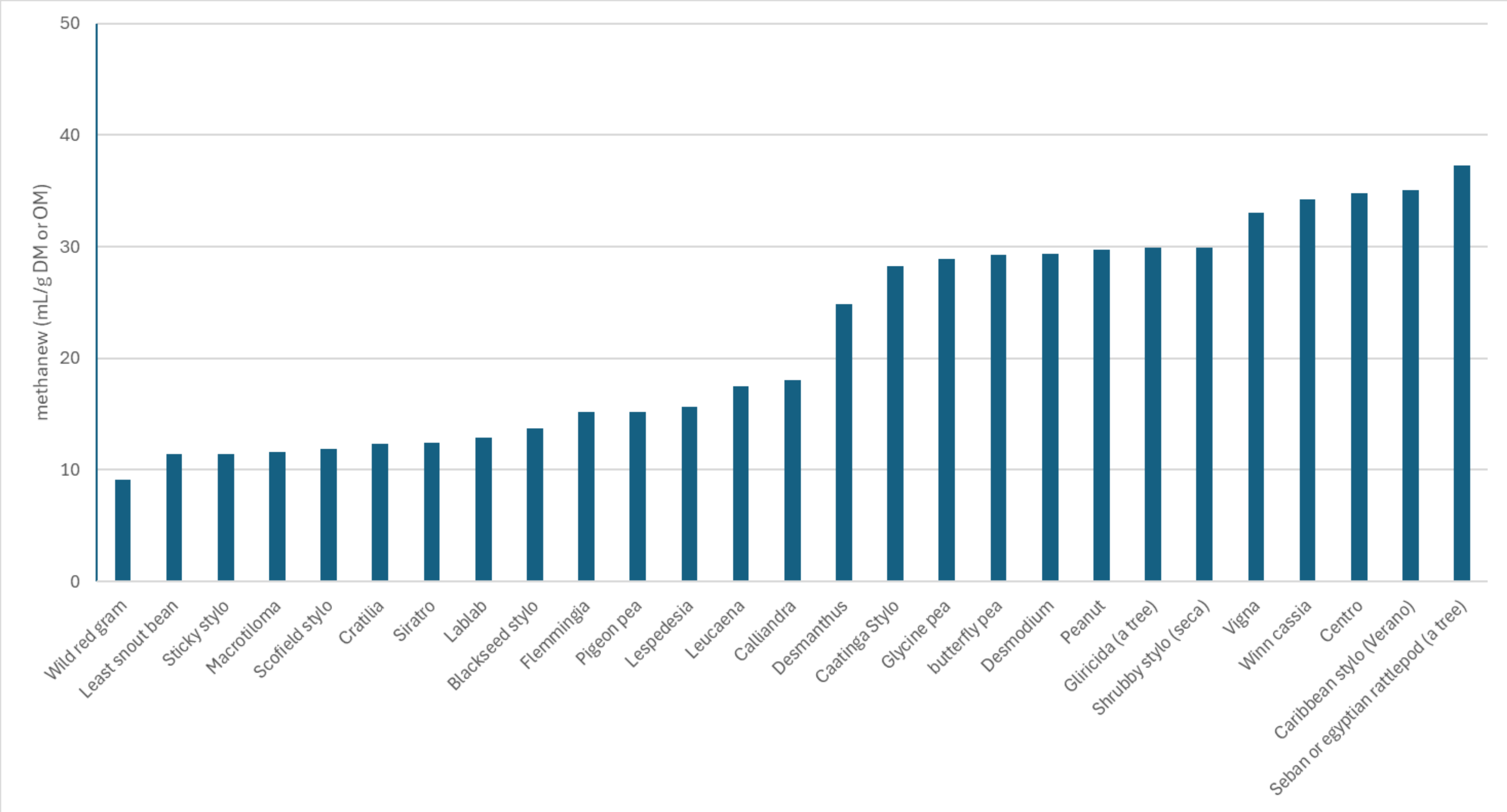
Table 3. *In vitro* methane production of tropical legumes. See Appendix 8.1 for references.

Common name	n	Methane (mL/g)*	Digestibility (%)	Methane (mL/g digested)†
Tropical legume	**144**	**26.8**	**59.0**	**49.9**
Agronomically important				
Siratro	1	12.4		21.0
Lablab	2	12.9		21.0
Leucaena	21	17.5	59.8	36.9
Desmanthus	26	24.8	56.1	43.5
Caatinga Stylo	5	28.3	58.5	48.4
Butterfly pea	6	29.3	60.8	48.8
Shrubby stylo (Seca)	5	30.0	55.3	54.6
Caribbean stylo (Verano)	5	35.1	60.8	57.5
Agronomically less important				
Wild red gram	1	9.1		23.2
Least snout bean	1	11.4		21.0
Sticky stylo	1	11.4		19.7
Macrotiloma	1	11.6		31.3
Scofield stylo	1	11.9		18.6
Cratilia	2	12.3		21.7
Blackseed stylo	2	13.7		22.2
Flemmingia	1	15.2		36.9
Pigeon pea	2	15.2		27.3
Lespedesia	1	15.7		31.5
Calliandra	13	18.0	49.2	36.6
Glycine pea	5	28.9	54.8	50.2
Desmodium	6	29.4	57.0	54.0
Peanut	19	29.7	64.0	43.8
Gliricida	6	29.9	59.3	53.0
Vigna	4	33.0	62.0	53.3
Winn cassia	4	34.3	61.0	56.0
Centro	9	34.8	61.8	57.1
Seban or Egyptian rattlepod	4	37.3	60.3	62.2
Tropical grasses	**99**	**30.7**	**-**	**-**

* Full reference list given in Appendix 8.1

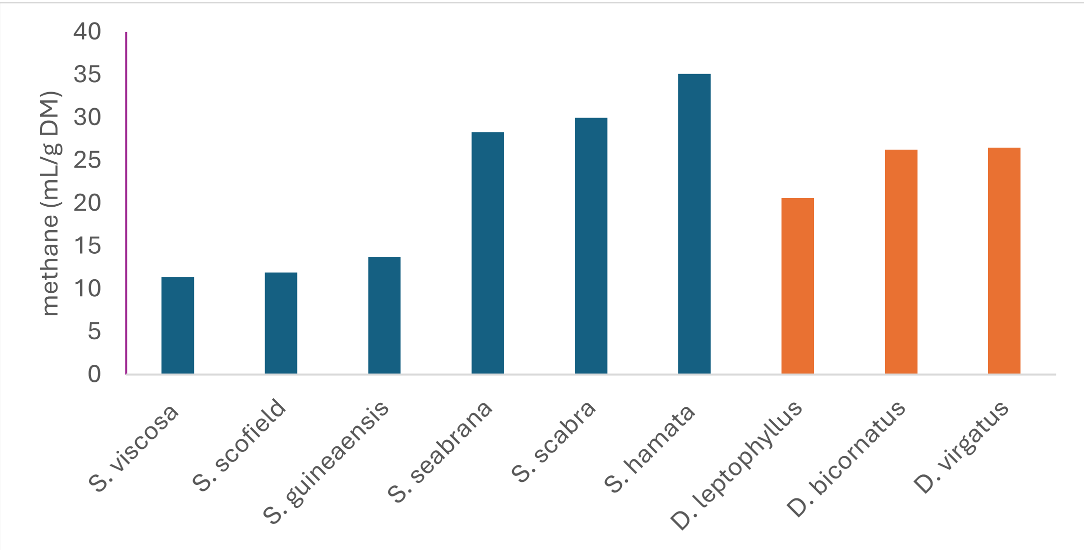
Depending on the study methane is expressed either on a DM basis or OM basis

Figure 5. Species variation in *in vitro* methane yield (mL/g DM or OM) of tropical legumes. See Appendix 8.1 for references.



Among the agronomically suited species, siratro (*Macroptilium atropurpureum*) and lablab (*Lablab purpureus*) had the lowest methane production (13 mg/g) of all tropical legumes. However, only one value was found for each species. Given their relatively widespread occurrence, further investigation is warranted into their antimethanogenic potential. Research on *Leucaena and Desmanthus* however is more thorough, and these two species demonstrated reduced methane production compared to the other tropical legumes. *Leucaena* with 21 datasets had a somewhat lower methane production (17.5 g/kg) than *Desmanthus* with 26 datasets (24.8 g/kg). However, within the *Desmanthus* genus, there are several agronomically important species with *D. leptophyllus* having the lowest methane production (20.6 mg/g) *in vitro* (Figure 6). The stylos (*stylosanthes*) showed a wide range in methane production (Figure 6). However, the species grown in northern Australia (*S. seabrana* (caatinga), *S. scabra* (shrubby) and *S. hamata* (Caribbean stylo) were not found to have antimethanogenic activity (31 mg/g) compared to the average for tropical legumes (25.4 mg/g).

Figure 6. Species variation in *in vitro* methane yield (mL/g DM or OM) for the *Stylosanthes* and *Desmanthus* genera (mean values across maturities). See Appendix 8.1 for references.



4.1.4.2 Temperate pasture species

Temperate pasture species with anti-methanogenic potential include legumes, brassicas, plantain and chicory (Table 4). A list of cited *in vitro* research publications is given in Appendix

8.1. Legumes are represented by a wide range of species and constitute the largest proportion of temperate data (Figure 7).

Across 163 datasets the mean methane production from temperate legumes was 34.9 mg/g DM or OM digested with a wide range from 4.0 to 74.0 mg/g. This value was higher than that observed for 141 comparisons of tropical legumes that averaged 25.4 mg/g (range 1.6 to 70.0 mg/d), but similar to the value for temperate grasses (38.3 mg/g). Within temperate legumes, biserrula (*Asrtalagus pelecinus*) was an outlier with methane yield of only 8.2 mg/g (n = 10). Of note was lucerne that ranked 8th out of 25 species evaluated and 14% lower than the value for subterranean clover. Sainfoin and birdsfoot trefoil were ranked 5th and 6th lowest for methane production. For species ranked higher than lucerne it was unlikely that they would elicit a reduction in methane under commercial conditions as the methane production was greater than 33 mL/g. When expressed relative to digestible material the yield was still well below that for other temperate legumes (10.4 mg/g). Among the remaining temperate legumes, there was a range in methane yield of between of between 20 and 45 mL/g (Figure 7). While the temperate legumes yielded higher methane values than the tropical species, it is important to note that the digestibility of temperate species is higher than that for tropical legumes, thus on a digestible DM basis, temperate legumes exhibit lower emissions than tropical legumes (Figure 7).

Figure 7. Species variation in *in vitro* methane yield (mL/g DM or OM) of temperate legumes. See Appendix 8.1 for references.

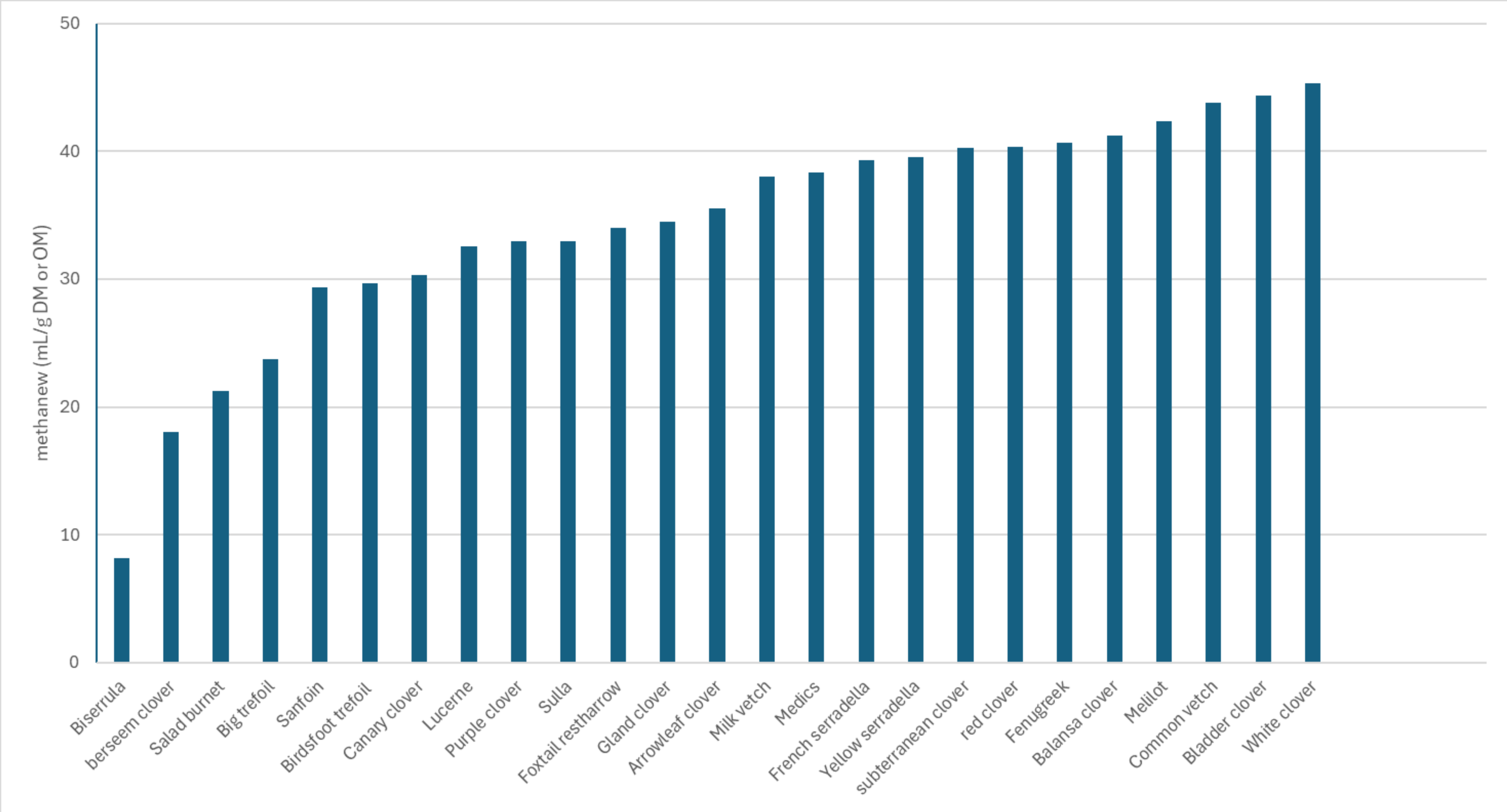


Table 4. ***In vitro*** **methane production of temperate species. See Appendix 8.1 for references.**

Common name	N*	Methane (mL/g) #	Digestibility (%)	Methane (mL/g digested)*
Temperate legumes	**163**	**34.9**	**69.6**	
Agronomically important				
Biserrula	10	8.2	71.1	10.4
Sainfoin	9	29.3		
Birdsfoot trefoil	9	29.7		
Lucerne	14	32.6	64.3	47.3
Sulla	7	33.0	65.9	
Medics	18	38.3	73.0	53.2
French serradella	7	39.3	70.8	60.7
Yellow serradella	7	39.5	65.0	59.0
Subterranean clover	18	40.2	67.7	53.1
Red clover	3	40.3		
Fenugreek	10	40.7	71.3	55.0
Balansa clover	7	41.2	68.6	60.7
Common vetch	6	43.8	0.0	62.5
Bladder clover	6	44.3	68.0	62.8
Agronomically less important				
Berseem clover	1	18.0		24.4
Salad burnet	4	21.3		
Big trefoil	4	23.8		
Canary clover	3	30.3		
Purple clover	2	33.0	62.8	54.1
Foxtail restharrow	2	34.0	71.4	48.3
Gland clover	2	34.5	67.5	52.2
Arrowleaf clover	1	35.5		
Milk vetch	2	38.0		52.4
Melilot	8	42.4	70.9	57.9
White clover	3	45.3	69.9	
Brassica	21	40.2	68.7	49.7
Kale	2	48.5		
Rape	7	40.7	71.2	45.2
Turnip	10	40.4	68.5	54.3
Field mustard	2	29.5	67.5	45.2
Chicory	**17**	**35.5**	**69.0**	**51.4**
Plantain	**9**	**28.**9		
Temperate grasses	**65**	**38.3**	**71.1**	**53.9**

* Full reference list given in Appendix 8.1

Depending on the study methane is expressed either on a DM basis or OM basis

4.1.4.3 Other species

Li *et al.* (2025) assessed a number of other species with known concentrations of secondary plant compounds. The trial was designed to determine if combinations of plant species with different modes of action could result in an additive effect on methane yield *in vitro*. The compounds included tannins and saponins. Mixes containing plantain plus a range of legumes had somewhat lower emissions (29.9 mL/g) than those where plantain was replaced with chicory (33.2 mL/g). This supported the observation that plantain produced less methane (29.7 mL/g) than chicory (33.5 mL/g) when they were incubated as the sole forage and indicated that the legumes had no effect on reducing methane in the mixes. These values are very similar to those obtained in South Australia and Western Australia (MLA 2015) but higher than those reported by Verma *et al.* (2022) in Europe.

Ten brassica cultivars of turnip, rape, canola, kale and wild turnip were evaluated in a single publication (MLA 2015) and recorded in South Australia and Western Australia. Mean methane yield was 35.3 mL/g, which was similar to the value for perennial ryegrass in the same study. This was somewhat surprising given the results from *in vivo* data in New Zealand (Sun *et al.* 2015) where they recorded a 22% reduction in methane yield in sheep. However, a lack of anti-methanogenic effect was also observed by Williams *et al.* (2016) with dairy cows in Victoria.

4.1.5 Low methane pasture species – *in vivo* studies

Forty-nine *in vivo* studies were included in the analysis amounting to 157 individual observations. A list of cited references for this section is given in Appendix 8.2. The antimethanogenic effect of the target species was assessed in terms of methane production (g/day) and the percent reduction in methane production and methane yield (g/kg DMI). In contrast to the *in vitro* data, most studies included a control treatment that allowed for meaningful % reductions in methane production or yield to be calculated. There were insufficient data to evaluate methane yield per unit of digestible intake. Most observations were made on non-lactating cattle (83), with 65 made on sheep and just 10 observations with dairy cattle (Table 5). On average, the reduction in methane yield for sheep was higher than for cattle. However, 22 of the 66 comparisons with sheep were for brassicas with a mean reduction in methane yield of 22%. In comparison, there was only one comparison for brassicas in cattle, and it did not show a reduction in methane yield. Most dairy data were related to supplements as opposed to pasture species and mixtures and not included in this analysis. Open path respiration chambers represented the predominant method for measuring methane (100) with SF6 the second most widely used method (47). A small number of measurements were made with other systems including poly tunnel (field-based portable airtight structure approximately 10 x 4 M acts like a large respiration chamber), field-based laser, and portable accumulation chamber (Table 4). These data were often associated with higher errors and widely differing mitigation response.

Table 5. *In vivo* methane data according to animal species and measurement method. See Appendix 8.2 for references.

	N*	Methane yield (g/kg DM)	Reduction in methane (% of control)
Data by animal species			
Beef	84	22.5	8.1
Dairy	10	19.9	15.4
Sheep	68	17.9	16.0
Data by measurement method			
Open circuit respiration chamber	102	18.1	7.2
Sulphur hexafluoride	45	25.7	4.9
Poly tunnel	1	23.5	29.2
Open path laser	3		22.4
Portable accumulation chamber	7	16.3	18.8

* Full reference list given in Appendix 8.2

In assessing the reduction in methane across different species and numerous publications, biases can become important. The standard approach for *in vivo* data is to compare the emission of the test species against the control expressed as a percent reduction. However, the response is highly dependent upon the emission from the control species. A large antimethanogenic effect may be apparent even if the absolute value of the treatment species remains above the NGGI value of 20.7 g/kg DMI assigned to non-antimethanogenic species. Table 6 summarises the combined animal data for methane yield and percent reduction in yield for data collected in respiration chambers across both tropical and temperate pasture species. When livestock species were considered separately, there were few specific inconsistencies, and combining them led to more meaningful interpretation. For clarity, mitigation was classed as None (< 0% mitigation), Low (0 to 5% mitigation, Med (5 to 10% mitigation) and High (greater than 10% mitigation; Table 6).

Table 6. *In vivo* methane yield (g/kg DM) and reduction in methane (% of control) from antimethanogenic pasture species for cattle and sheep – respiration chamber data*.

Common name	Rank#	n	Methane yield (g/kg DMI)		Reduction (%)		
			Control	Treatment	Min	Max	Mean
Tropical legume		**44**	**22.8**	**19.9**	**-57**	**61**	**11.7**
Agronomically suitable							
Leucaena	High	18	23.2	18.0	-2.1	61.7	21.9
Burgundy bean	Low	2	19.0	18.4	-1.1	7.4	3.2
Desmanthus	Low	6	20.35	19.8	-0.5	8.4	2.9
Stylo	Low	3	21.0	21.0	-11.6	16.3	-1.4
Agronomically less suitable							
Lespedeza	High	3	17.6	14.9	4.5	21.6	15.2
Glyricidia	High	1	31.0	26.9	-	-	13.2
Flemingia	High	2	22.2	19.3	7.4	18.6	13.0
Styzolobium	High	1	37.0	33.0	-	-	10.8
Calliandra	Med	3	23.6	21.8	-25.4	29.4	6.5
Mimosa	Med	1	37.0	35.0	-	-	5.4
Vigna	Low	1	22.2	22.1	-	-	0.6
Dolichos	None	2	18.9	20.1	-9.5	-3.7	-6.6
Temperate grass		**7**	**19.1**	**17.3**	**1.0**	**21.2**	**10.0**
Ryegrass	Med	7	19.1	17.3	1.0	21.2	10.0
Temperate legume		**19**	**19.2**	**18.7**	**-15.0**	**24.4**	**2.5**
Biserrula	High	1	13	7.17			43.1
Sainfoin	Med	3	25.7	23.8	-0.8	14.9	6.9
Lucerne	Low	4	21.2	20.3	0.0	9.5	4.2
Red clover	Low	1	28.4	28.0	-	-	1.4
French Serradella	None	1	13.5	13.5	-	-	0.0
Birdsfoot trefoil	None	1	28.4	28.9	-	-	-1.8
Common vetch	None	3	20.0	21.0	-5.9	5.0	-5.0
Bladder clover	None	1	13.5	14.3	-	-	-5.9
Brassica	**High**	**22**	**21.4**	**16.3**	**-13.1**	**63.6**	**24.9**
Rape	High	14	21.4	15.0	12.4	63.6	30.7
Leafy turnip	High	2	21.2	16.1	14.6	33.3	23.9
Swede	High	1	22.0	16.9	-	-	23.2
Radish	High	1	21.0	16.3	-	-	22.4
Kale	Med	1	22.0	19.8	-	-	10.0
Bulb turnip	Low	3	21.4	20.5	-13.1	20.5	4.6
Forage herb		**4**	**23.9**	**20.6**	**0.5**	**28.9**	**13.6**
Chicory	Med	2	23.6	22.0	0.5	11.7	6.1
Plantain	High	2	24.3	19.2	13.3	28.9	21.1
Chenopod		**4**	**8.3**	**7.8**	**-14.6**	**14.8**	**0.1**
Rhagodia	High	1	9.6	8.2			14.8
Old man saltbush	Low	1	9.6	11.0			-14.6

* Full reference list given in Appendix 8.2

None < 0%, High 0 to 5%, Med, 5 to 10%, Low < 5% based on published inclusion level

4.1.5.1 Tropical legumes

Within tropical legumes, *Leucaena* stood out as the most promising species to reduce methane emissions with a 22% reduction observed across 18 comparisons. All other agronomically useful tropical legumes were ranked Low or None for mitigation. While there has been considerable *in vitro* Australian research on *Desmanthus* showing promising reductions in methane production of 43%, the *in vivo* data suggests only a small reduction in methane yield of 3%. A field study of methane production from cattle grazing buffel grass or buffel grass/*Desmanthus* pastures on a commercial property showed a 5 to 7% reduction in methane yield, but only in the wet season when the *Desmanthus* was actively growing and in leaf (Charmley 2025). These data were not included in the review as they were collected using gas emissions monitoring units (GreenFeed, C-Lock inc., Rapid City, South Dakota, USA). Several agronomically unimportant legumes showing reductions in methane yield in excess of 10% were noted.

Stylos are widely distributed across pastures in northern Australia yet there were only two comparisons conducted in Australia. This may be because *in vitro* data has not demonstrated any potential for reducing methanogenesis (Durmic *et al.* 2016) in the key stylo species that are widely used across northern Australia. Kennedy and Charmley (2012) found that when Caribbean stylo (*S. hamata*) hay was included at 20 and 40% in cattle diets based on Rhodes grass hay (CP = 10% DM) methane yield increased by 9 and 11%, respectively. However, in an African study (Assouma 2023) when low quality grass was supplemented with 25% *S. hamata* methane yield decreased by 16%. The different response between these two studies may have been related to the CP content of the grass. Addition of tropical legumes to low quality grasses has been shown to reduce methane yield through a combination of increased DM intake and improved ruminal digestion (Suybeng *et al.* 2020). This effect is muted when the CP of the companion forage is higher (Suybeng *et al.* 2021). Reasons for lowered methane production simply in response to CP have been attributed to increased rate of passage from the rumen and a shift to increased propionate production in the rumen (Archimede *et al.* 2016). The need for *in vivo* assessment to confirm the effect of stylos in the diet on methane production is a priority. Given the widespread use of stylos in tropical pastures and its potential to reduce methane intensity by increasing animal production, this is a species that requires further research into its possible antimethanogenic potential.

Two tropical legumes, lablab (*Lablab purpureus*) and siratro (*Macroptilium atropurpureum*), of some agronomic importance were shown to reduce methane *in vitro,* but there was only one *in vivo* study that found no reduction in methane compared to a tropical grass (Kennedy and Charmley 2012). These potentially minor-use species should be investigated to determine if the *in vitro* response can be replicated *in vivo*. *Calliandra* is a tropical shrub, similar in growth habit to *Leucaena*. Overseas research with livestock has shown mixed results, with some studies showing no effect (Tiemann *et al.* 2008b) while another study showed *Calliandra* reducing methane by 30% when included in a grass diet (Mwangi *et al.* 2024). The opportunity for *Calliandra* as novel species should be explored, as it could offer an alternative to *Leucaena*.

There was no respiration chamber data comparing tropical grasses. One report using the poly tunnel method (Gaviria-Uribe *et al.* 2020) method compared a *Urochloa* hybrid with *Dicanthium aristatum* and observed a 16% reduction in methane yield.

4.1.5.2 Temperate legumes

Within temperate legumes, the greatest reduction in methane yield (43%) was observed for biserrula with just one comparison (Hutton *et al.* 2014). A subsequent study (MLA 2015) found a small reduction in methane production, but there was some uncertainty regarding the veracity of the data (Vercoe P, pers. Comm, 2024). However, the significant reductions in methane production *in vitro*, lend convincing evidence that biserrula is highly methanogenic. Other species exhibiting a reduction in methane yield were (in order of methane reduction) sainfoin, lucerne and red clover and these were classified as medium to low in terms of emissions reduction. There were very few comparisons made for lucerne using respiration chambers (n = 4) although there were four further comparisons for lucerne using the SF6 technique. These were all from North American grazing studies and generally showed an increase in methane production in response to lucerne, likely due to improved nutritive value and intake (Chaves *et al.* 2006; Stewart *et al.* 2019). Surprisingly, given the importance of lucerne in southern Australia, the *in vivo* data on its antimethanogenic potential is sparse. There was a larger number of comparisons for *in vitro* data (n = 14) showing that lucerne was ranked 8th lowest for methane production among 25 temperate legumes. On the balance of evidence, it is concluded that lucerne likely reduces methane production and also has a marked effect on methane emissions intensity through increased animal gain. Therefore, lucerne is included among the prospective species for reducing methane emissions from pastures. It is recommended that a priority for future research should be to assess methane emissions from lucerne using respiration chambers.

4.1.5.3 Other species

Among the brassicas, the majority of comparisons were made on rape (*Brassica napus*), a leafy variety. From 13 comparisons the reduction in methane yield averaged 27% when the brassica comprised 87% of the diet. The single published Australian study was conducted on forage rape but the authors found no reduction in methane yield of dairy cows. A recent report from University of New England found a 43% reduction in methane production in sheep from a leavy brassica cultivar (D. Sitiene, pers. Comm.). It appears that leafy cultivars elicit a higher reduction in methane than the bulb cultivars (turnip, swede). Based on some encouraging data, albeit mostly from overseas, further research is required with brassicas to determine if they could provide a low emission forage for intensive pasture-based finishing for lambs and cattle. It will also be important to determine the mode of action that could be due to either nitrates or glucosinolates, both of which have anti-nutritional characteristics. The recent increased interest in brassicas as a winter feed source suggests that the area of brassicas grown in the high rainfall zone of southern Australia is likely to increase (Watt and Bell 2024).

Plantain and chicory are two species that reduce methane by alternative modes of action to legumes. Thus, there is potential for these to be used in combination with legumes and have an additive effect on methane yield reductions. Various theories have been tested to elucidate the mode of action including the role of saponins as well as increased rumen outflow rate, due to a high proportion of pectins in the water-soluble carbohydrate fraction (Verma *et al.* 2022, Woodmartin *et al.* 2024). In the small number of *in vivo* studies evaluated, plantain was more effective than chicory in reducing methane (21% versus 6%).

Among other potential antimethanogenic species, the high water soluble carbohydrate *Lolium* cultivars reduced methane yield by about 10%. These ryegrasses can elicit three mechanisms whereby methane production is reduced. Firstly, increasing the soluble carbohydrate shifts the balance away from acetogenic and towards propionogenic rumen fermentation, which of course will reduce methane (Purcell *et al.* 2014; Warner *et al.* 2016). Secondly, there is a simple diluting effect on the CP in the diet as the carbohydrate content increases in very high digestibility grasses (Staerfl *et al.* 2012; Warner *et al.* 2016). Thirdly, highly digestible forages (>70% DMD) exhibit rapid rates of passage from the rumen minimising the opportunity for the archaea to synthesise methane from hydrogen and carbon dioxide.

Members of the Chenopodiaceae family make a small but locally important contribution to sheep production in the drier parts of Australia with saline soils. While old man saltbush was not found to reduce methane, *Rhagodia* reduced methane by 15% possibly through the action of saponins (Li *et al.* 2018).

4.1.5.4 Tropical and Temperate Legumes: SF_6 data

Twelve comparisons were made for tropical legumes using the SF6 technique (Table 7). Again, *Leucaena* was the most antimethanogenic tropical legume (17% reduction). Two relatively well adapted species (groundnut and pigeon pea) did not reduce methane, but another *Arachis* species did. There were 24 SF_6 comparisons for temperate legumes. Several species were found to have large reductions in methane yield of between 8 and 44%. Species with agronomic potential like sainfoin (*Onobrychis viciifolia*) and birdsfoot trefoil (*Lotus corniculatus*) did not reduce methane *in vivo* even though they showed potential from *in vitro* gas. Lucerne exhibited a large increase in methane yield, with data coming from the USA and Canada.

Table 7. *In vivo* methane yield (g/kg DM) and reduction in methane (% of control) from antimethanogenic pasture species for cattle and sheep – SF_6 data*.

Common name	n	Methane yield (g/kg DMI)		Reduction (%)		
		Control	Treatment	Min	Max	Mean
Tropical legume	**14**	**29.0**	**26.2**	**-70.0**	**44.4**	**8.2**
Agronomically important						
Leucaena	1	-	-	-	-	17.2
Agronomically less important						
Creeping peanut	4	37.0	32.3	0	27.0	12.8
Lespedeza	4	27.3	24.1	3.3	27.1	11.8
Groundnut	1	22.9	25.3	-	-	-10.5
Pigeon pea	2	28.0	27.0	-70.0	44.4	-12.8
Temperate grass	**1**	**25.6**	**25.7**	**-**	**-**	**-0.4**
Ryegrass	1	25.6	25.7	-	-	-0.4
Temperate legume	**19**	**19.2**	**18.7**	**-15.0**	**24.4**	**2.5**
Agronomically important						
Sulla	1	24.6	19.5	-	-	20.7
Sainfoin	4	32.8	30.7	2.9	16.8	7.9
Birdsfoot trefoil	6	27.5	28.0	-21.6	11.1	-5.2
Lucerne	4	26.0	29.9	-45.5	26.5	-21.8
Agronomically less important						
Salad burnet	1	37.8	21.3	-	-	43.7
Cicer milk vetch	1	37.8	31.8	-	-	15.9
Berseem clover	1	15.5	13.8	-	-	11.0
Red clover	2	24.5	22.3	-5.5	14.6	10.9

* Full reference list given in Appendix 8.2

4.1.6 Regional suitability and adoption of key species

Following the review of the adapted species that could be included in pastures, seven species or genera were identified as potential candidates likely to have a meaningful effect on methane emissions from pastures nationally. The initial selection was based on their potential to reduce methane yield and their agronomic importance. These species are given in Table 8 together with the number of data comparisons, the range in mitigation, and the mean methane inhibition yield (g/kg DMI) expressed as a percentage of the control emission within each publication. The mitigation at 100% inclusion is theoretical and included to allow the proportional mitigation to be determined at any inclusion rate in the diet.

Table 8. Prospective candidate species/genera to reduce methane emissions from grazing animals

	Rank*	n	Mean published mitigation (%)	Range in mitigation (%)	Mean diet inclusion level (% DM)	Mitigation at 100% inclusion level (%)
Lucerne	Med	4	5.2	-4.8 to 9.5	31	16.8
Brassicas	High	23	22.3	-13.1 to 63.6	81	27.5
Leucaena	High	18	21.9	-2.1 to 61.7	43	50.9
Stylosanthes	Low	3	-1.4	-11.6 to -16.3	28	-5.0
Desmanthus	Med	6	2.9	-0.5 to 8.4	26	11.2
Biserrula	High	1	43.0	-	100	43.0
Plantain	High	2	21.1	13.0 to 28.9	100	21.9

*high >20%, Med, 10 to 20%, Low < 10% based on 100% inclusion level

A further three species were of local importance (minor use) but unlikely to have a marked effect on grazing emissions nationally. These were high water soluble carbohydrate (WSC) ryegrass cultivars, sainfoin (*Onobrychis viciifolia*), and *Rhagodia* (*Rhagodia preissii*). The number of comparisons were relatively few with mitigation ranging from 7 to 21 % (Table 9).

Table 9. Minor use candidate species to reduce methane emissions from grazing animals

	Mitigation classification*	n	Mean published mitigation (%)	Range in mitigation (%)	Mean inclusion level (% DM)	Mitigation at 100% inclusion level (%)
Ryegrass	Med	7	10.0	1.0 to 21.2	100	10.0
Sainfoin	Low	3	6.9	-0.9 to 14.9	100	6.9
Rhagodia	High	2	14.8	-	26	53.8

*high >20%, Med, 10 to 20%, Low < 10% based on 100% inclusion level

4.1.6.1 Suitability of key species for potential adoption

Having determined the seven prospective species, their agronomic requirements and suitability as livestock feeds were assessed and the outcomes summarised in Table 10. Of primary importance is the suitability of a particular species to a particular area. The introduction or expansion of anti-methanogenic species is primarily dependant on rainfall. In southern Australia introduction of new species is only considered practical and/or economically viable in medium or high rainfall regions on the more coastal fringes of southern Australia where average annual rainfall is considered sufficiently reliable to support the establishment of new species. Thus, the large areas of low rainfall rangelands in central and southern Australia (agro-climatic classes 'G' and 'E6 from Figure 8) are considered out of scope for the introduction of new species with anti-methanogenic potential. In northern Australia, *Desmanthus* and stylos are economically viable in rainfall zones as low as 450 mm. This review focuses on areas of northern Australia above 450 mm.

Within medium and high rainfall zones, factors such as soil type, rainfall, evapotranspiration, minimum and maximum temperatures are all important in assessing the agronomic suitability of pasture species. Conditions in northern Australia are typically characterised by extreme seasonal rainfall variation, with wet summers and dry winters. Soils are generally of low fertility and much of the north is suitable for extensive grazing with stocking rates varying between 5 to 500 ha/AE (Charmley *et al.* 2025). However localised areas of fertile soils allow for more intensive livestock production when rainfall is adequate of where there is access to irrigation.

Table 10. Optimum conditions to produce low emissions species/genera in Australia and limitations for livestock

	Rainfall (mm)	Temperature range (°C)	Soils	Soil pH	Limitations for livestock
Lucerne*	250 to 1,200	10 to 25, depends on winter activity level	Well drained sands to moderately heavy clays	Slightly acid to alkaline	Can cause bloat in livestock
Brassicas[#‡]	>600	Temperate humid livestock zone, autumn sown crops	Well drained light to heavier soils	> 4.5	Avoid grazing immature crops- risk of nitrate poisoning for cattle
*Leucaena**	>650	Susceptible to frost	Well drained heavier soils such as vertosols and sodosols	Neutral to alkaline	Risk of mimosine poisoning – inoculate cattle with *Synogistes jonesii.*
*Stylosanthes**	500 to 1,000	Susceptible to frost	Lighter soils such as kandosols, except *for S. seabrana* that prefers heavier soils	4 to 8	Suited to extensive grazing conditions
*Desmanthus**	>400	Defoliated by frost	Heavier soils such as vertosols and sodosols	Neutral to alkaline	Suited to extensive grazing conditions
*Biserrula**	300 to 700	Moderate frost tolerance	Well drained, light or sandy soils such as chromosols and dermosols	4 to 7	May cause photosensitisation in sheep
Plantain	>600	Temperate humid livestock zone, sown in mixtures often with chicory	Well drained light to heavier soils	4 to 8	Deep rooted, high in micronutrients

Source:
* Pastures Australia (2025)
[#] MLA (2025)
[‡] Bell *et al.* (2020)

Temperate Australia supports a range of mixed farming systems with livestock and cropping co-existing in selected areas. As in the north, rainfall is a major determinant of the intensity and balance of production systems. Typically, grazing enterprises still dominate the land use in terms of number of hectares, although cropping predominates in areas of higher fertility where topography is suitable. Mediterranean conditions in the south-western quadrant of the country are suited to mixed farming systems with sheep more important than cattle. Hutchinson *et al.* (2005) classified Australia into agroclimatic classes (Figure 8). Within the three bio-regions defined in this report (tropical, temperate and Mediterranean) the predominant classes according to Hutchinson *et al.* (2005) are given in Table 11.

Figure 8. Agroclimatic classes of Australia showing the three regions in the review (Hutchinson *et al.* (2005)

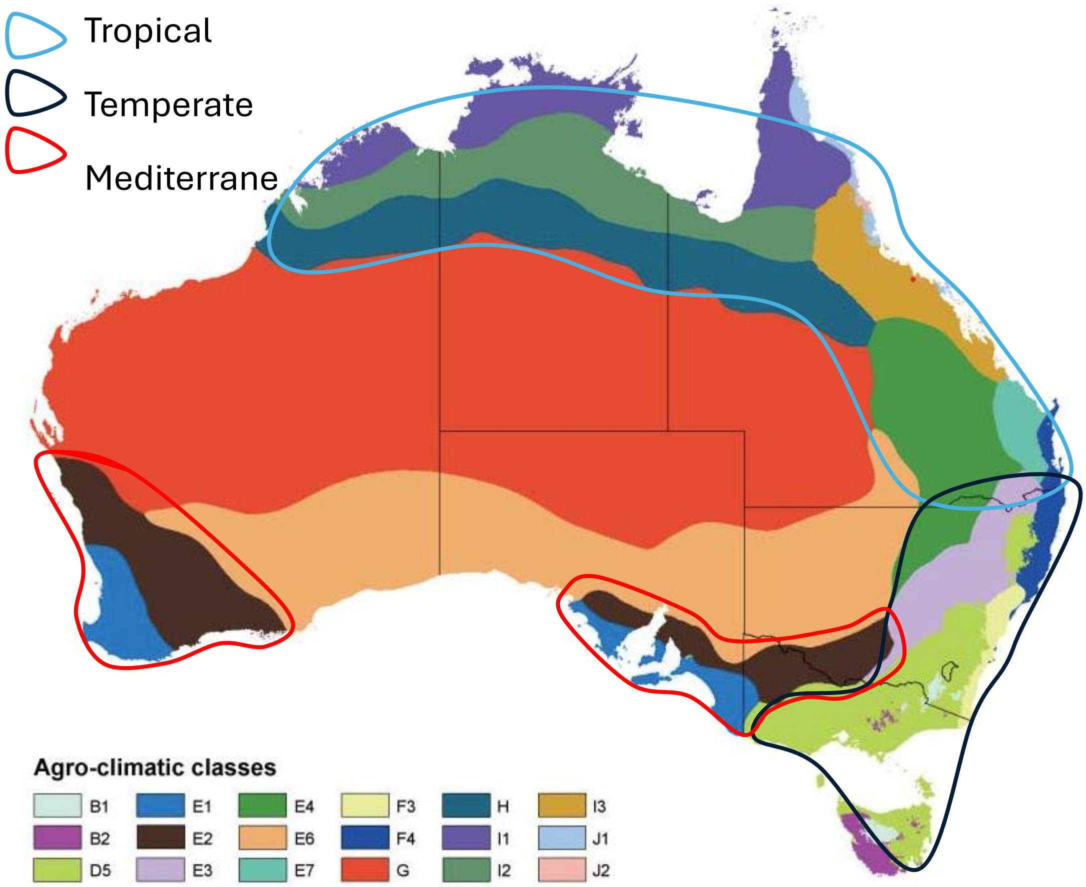


Table 11. Agroclimatic classes of major importance for livestock (adapted from Hutchinson *et al*. (2025)

Bioregion	Agroclimatic class	Location and land use
Tropical	E4	Unique in the World to sub-tropical continental eastern Australia and associated with the Brigalow belt of Queensland and NSW. Cropping and sown pastures
	E7	Maritime sub-tropical areas in southern Queensland. Cattle gazing
	I1	NT, northern WA and Cape York Peninsula. Predominately rangeland.
	I2	Occurs inland of I1, predominantly rangeland
	I3	Occurs in the coastal and hinterland areas of north-east Qld, south of Cape York Peninsula. Sugar, cropping and rangelands
Temperate	D5	Tasmanian lowlands, southern Victoria, southern and northern Tablelands of NSW. improved and native pasture
	E3	Western slopes of NSW and part of the North Western Plains. Winter cereals and summer crops, grazing
	F4	NSW North Coast, extending to southern Qld and the Great Sandy province. Horticulture, sown pasture and tourism. Potential for wheat, cotton and maize
Mediterranean	E1	South-west WA and southern SA. Forestry, horticulture, winter cropping, improved pastures
	E2	Inland of E1 in south-west WA, southern SA, north-west Victoria

4.1.6.2 Agronomic considerations of tropical species

The areas where the seven species/genera considered to be most effective in reducing methane emissions from grazing animals are defined by climate and soil attributes summarised in Table 11. Three genera are of specific interest in northern Australia: *Leucaena, Stylosanthes* and *Desmanthus*.

Leucaena (*L. leucocephala*) is adapted best to deep fertile soils with annual rainfall over 600 mm (MLA, 2021). It can contribute between 30 to 50% of the diet during and following the wet season over a period of 5 to 8 months (Table 12; (Dixon and Coates 2008; Charmley *et al.* 2023a). As a small tree it can grow to considerable heights and is typically cut back to retain the edible leaf within reach of cattle. Grown in rows within grass-dominated paddocks it can persist for over 30 years. Due to its deep tap root it is relatively drought tolerant and will produce green shoots throughout approximately 5 to 8 months of the year (Charmley *et al.* 2023a). As a row crop it responds to fertilizer and requires a higher level of management than stylos and *Desmanthus*. Modern cultivars have been developed that are psyllid resistant (Redlands), and high yielding (Wondergraze). *Leucaena* cannot be grown at scale in Western Australia due to restrictions placed on *Leucaena* sowing owing to its weed potential. The presence of mimosine in *Leucaena* and its breakdown products in the rumen has resulted in cattle poisoning and deaths when naive cattle are exposed to fresh young *Leucaena* (Jones and Hegarty, 1984; Dalzell *et al.* 2012). The development of a rumen inoculant containing the bacteria *Synergistes jonesii* has been used to provide protection by converting mimosine to non-toxic secondary compounds in the rumen. Current thinking suggests that strains of *S. jonesii* are widespread in northern Australia and cattle can acquire passive immunity to mimosine from the environment.

Leucaena is the most widely studied tropical legume of relevance to the Australian livestock sector. Since its introduction in the mid-20th century, it has been shown to increase animal productivity by 50 to 150 % (Harrison *et al.* 2016; Tomkins *et al.* 2019; Charmley *et al.* 2023a) and reduce methane *in vivo* by 16% (Australian data only) and 23% worldwide with 25 comparisons. Stifkens *et al.* (2022) demonstrated a dose response to *Leucaena* inclusion in a Rhodes grass diet with maximum methane inhibition of 18.5% and maximum intake response (+50%) at 36% inclusion. While the trial was not designed to determine performance the LWG response was 0.2 kg/d for every 10% increase in *Leucaena* in the diet.

In spite of these credentials, it is estimated that only approximately 123,000 ha have been established with *Leucaena* (Beutel *et al.* 2018). It is estimated that about 13 million ha of northern Australian could grow *Leucaena* (Charmley *et al.* 2025) and Mitchell *et al.* (2025) indicated that approximately 62% of the northern beef herd could have access to *Leucaena* if adoption rates were increased. Reasons for poor adoption rates are many including high cost of establishment and ongoing management, availability of seed, lack of available machinery, susceptibility to pests and frost, and crop failure. Nevertheless, with the development of new cultivars and widespread interest in the crop, increased rates of adoption are envisaged, particularly if methane abatement schemes are developed with financial incentives.

The stylos are the most widely adopted tropical legume being found in over a million ha of extensive grazing. The potential for increased use of stylos to improve the feed value of northern pastures is large with potentially 50 million hectares of land with suitable soils and climatic conditions. However, limited research suggests that the currently used stylo cultivars may not be antimethanogenic (Kennedy and Charmley 2012).

Nutritionally stylos are high in CP with livestock browsing the leaves and green stems in search of additional protein particularly in the dry season when the CP of grasses are below 5%. Coates (1996) showed that stylos accounted for over 40% of the diet for nine months of the year in the seasonally dry tropics (Table 12). Research has shown a 30 to 270% response in animal productivity when pasture with and without stylos are compared (Bowen and Rickert 1979; Gardener *et al.* 1993; Noble *et al.* 2000; Hill *et al.* 2009). Three species are agronomically important and vary in their edaphic and climatic optima: shrubby, Caribbean (*S. hamata*) and Caatinga (*S. seabrana*) stylos. In a recent review Mitchell *et al* (2025) showed that these stylo species have high potential for methane mitigation according to *in vitro* data for about 40% of the northern beef herd. The widespread adoption of stylos, their known improvement in turn-off weights and the uncertain antimethanogenic impact suggest they could contribute to reductions in methane intensity of beef production from northern grazing lands.

Table 12. Length of the grazing season for tropical legumes, their contribution to the diet and crude protein content.

	Months of legume intake	Diet (% legume)	Crude protein (% DM)
*Leucaena leucocephala**	5 to 8	30 to 50	20 to 25
Stylosanthes species[#]	6 to 9	20 to 50	20
Desmanthus species[‡]	5 to 7	30 to 40	15 to 25

* Dixon and Coates (2008); Charmley *et al.* (2023)

[#] Coates (1996)

[‡] Charmley (2025)

Several species of the genus *Desmanthus* have been developed for commercial release in northern Queensland (Gardiner 2016; Gardiner *et al* 2017), these include *D leptophyllus, D. virgatus* and *D. bicornatus*. These species are one of the few tropical legumes adapted to the clay soils prevalent in western Queensland. Adoption of these new cultivars is relatively recent, but it is estimated that there are over 100,000 ha now sown with *Desmanthus* species, mostly *D. leptophyllus* and *D. virgatus* in Queensland. There is also recent interest in *Desmanthus* for northern New South Wales (S. Boschma, personal communication). Although the area with established *Desmanthus* is currently small, it is estimated that 35 million ha of northern Australia is suitable for the commercial establishment of *Desmanthus* (Charmley *et al* 2025). Suybeng *et al.* (2019) reviewed the potential for *Desmanthus* in Queensland and concluded that the availability of cultivars of different *Desmanthus* species extend the geographic range for adoption and the use of mixed species in the pasture also extended the active growing season by exploiting the combination of early to late maturing types. Once established, *Desmanthus* can persist for years due to the production of large quantities of hard seed that germinate when growing conditions are optimised.

Nutritionally, the CP content of *Desmanthus* is approximately 20%, being higher in the leaf than stem (Mwangi *et al.* 2022). Active growth is initiated following rainfall in the warmer months and with advancing maturity, the CP content declines as the proportion of leaf is reduced. Nevertheless, the browsing habit of livestock grazing *Desmanthus* allows them to select for the more nutritious plant parts well into the dry season. Charmley (2025) observed that *Desmanthus* accounted for over 30% of the diet for approximately six months of the year, depending on the length of the wet season. Inclusion of *Desmanthus* in northern pastures can increase animal productivity by 10 to 30% (Gardiner and Parker 2012; Collins *et al.* 2016; Mwangi *et al.* 2021). Although published data for *Desmanthus* is scarce and the animal response appear less than that seen for stylos, anecdotal evidence from producers, suggest that the performance benefit may be more likely to be in the 25 to 30% range (N Kempe, personal communication).

In vitro data (n = 26) suggested that *Desmanthus* is antimethanogenic however, *in vivo* data suggested a smaller response in methane mitigation. Considering the potential widespread adoption of *Desmanthus*, the nutritional advantage and the modest impact on methanogenesis, Mitchell *et al* (2025) concluded that *D. virgatus* had high potential for methane production due to its widespread adaptability potentially reaching 77% of the northern cattle herd. *D. leptophyllus* was ranked as having medium potential to reduce methane emissions being adapted to areas accounting for 42% of the northern beef herd.

While Stylos, *Desmanthus* and *Leucaena* are best adapted to different areas of the north, there is considerable overlap between species in the geographical areas where they can be established. While *Desmanthus* is suited to the clay soils of western Queensland, it also occurs in areas where stylos are prevalent. Likewise, stylos are adapted to areas suitable for *Leucaena* production.

Siratro (*Macroptilium atropurpureum*) and Lablab (*Lablab purpurens*) are two other legumes of some importance in the north. These are prostrate vine-like annual legumes suited to higher rainfall areas. Both are of good nutritive value and reduce methane production *in vitro* more than other tropical legumes. While siratro is not purposefully included in pastures, it nevertheless can become a significant portion of the pasture and has weedy attributes. Lablab, on the other hand, is an important tropical legume and can be grown with high yielding crops like sorghum and maize.

4.1.6.3 Agronomic considerations of temperate species

Lucerne is grown across approximately 2.3 million ha mostly in New South Wales, Victoria, and South Australia, with about 400,000 ha seeded each year (Hudson 2017), albeit largely to replace areas that are taken out of lucerne production for a different component of the crop/pasture rotation. While a proportion is grown for hay and silage approximately 80% was grazed in New South Wales in the 1990s (McDonald 2003). More recent data were not available; however, it is assumed that this proportion remains relevant in 2025. A high yielding, high quality legume it prefers well drained soils and above 400 mm annual rainfall and is one of the most widely adopted pasture legumes in temperate Australia, with the exception of clover. It can be grazed for 7 to 9 months of the year (Table 13). Nutritionally, it is an excellent forage crop with CP content over 20% at the vegetative growth stage, declining with flowering to around 12 to15%. Digestibility is between 60 and 70% and the ME content varies between 10 and 12 MJ/kg DM (MLA, 2015). Lucerne yields in forage plots can exceed 20 tonnes DM/ha and the crop can be harvested at 3 to 4 week intervals for silage or hay . The high biomass production and nutritive value result in a 20 to 100% increase in animal performance per hectare compared to all grass or mixed swards depending upon the pasture conditions. Today's cultivars are more tolerant to grazing and can be successfully managed to achieve high animal output both individually and on a per ha basis. However, lucerne can be associated with frothy bloat when naive cattle are exposed to immature lucerne. This is due to the presence of saponins in lucerne that cause froth to build up in the rumen and can be fatal. It is the presence of saponins that may also reduce the production of methane in cattle grazing lucerne.

Considering the importance of lucerne and the improvements in animal performance observed, as well as a yet to be confirmed antimethanogenic potential, it is a potential candidate to reduce methane intensity from grazing livestock in temperate Australia. However its current place in arable, mixed farming systems and the fact it competes with crops for land area means it is uncertain how much more area might reasonably be sown to lucerne. Breeding of new varieties of lucerne with heightened anti-methanogenic properties might be the most logical way to decrease methane production through lucerne, as this would naturally replace existing lucerne paddocks which typically last around 5-7 years before being replaced. Assessment of lucerne cultivars for their potential to reduce methane in animal studies is a priority for future research.

Table 13. Length of the grazing season for temperate species, their contribution to the diet and crude protein content.

	Months of legume intake	Diet (% low emissions species)	Crude protein (% DM)
Lucerne	7 to 9	20 to 50	20 to 30
Biserrula	5 to 7	30 to 60	15 to 25
Brassicas	4 to 9	50 to 90	15 to 25

There are a wide range of other legume species that are found in temperate pastures including lotus (*Lotus uliginosus syn. L. pedunculatus*), birdsfoot trefoil (*Lotus corniculatus*), clovers, sainfoin (*Onobrychis viciifolia*), and sulla (*Hedysarum coronarium*) (Badgery *et al.* 2023). However, these species are lower yielding than lucerne and while they may be regionally important, they do not have the widespread adoption of lucerne. Badgery *et al.* (2023) concluded that lotus was the most widely grown of these species, with potentially 100,000 ha in New South Wales. Some of these such as lotus, birdsfoot trefoil and sainfoin exhibit modest reductions in methane when fermented *in vitro* (Durmic *et al.* 2016; Li G 2025) and also in trials with animals (Muir *et al.* 2020; MacAdam *et al.* 2022). Sainfoin was included as a minor use species based on its antimethanogenic potential.

Biserrula is a temperate legume adapted to the mediterranean bioregion and stands out as a legume suited to the WA wheat-sheep belt. It has a marked effect in reducing methane *in* *vitro* (Banik *et al.* 2019). Methane production was around 10 mg/kg DM compared to 40 mg/kg DM for subterranean clover at similar digestibility. Batch culture data (MLA 2015; Li *et al.* 2025) also showed very low methane production (4 to 11 mL/g DM fermented), however data using Rusitec fermenters (MLA 2015) revealed less clear results. When biserrula substituted subterranean clover, methane production was only reduced at the 50% substitution level. A similar result was observed by Li *et al.* (2025) when biserrula was incubated in mixes with other species (22 to 34 mL/g DM incubated) including chicory, plantain, Phalaris, cocksfoot and tall fescue. *In vivo* trials have produced equivocal results. Hutton *et al.* (2014) observed a 42% reduction in methane production and 24% reduction in methane yield when fresh biserrula was fed to sheep. On the other hand, MLA (2015) found that when biserrula hay replaced serradella hay in sheep diets there was no reduction in methane yield, although there was a linear effect of biserrula inclusion level (0 to 100%) and methane per MJ of ME. Emissions data from this trial were unusually low for both the serradella and biserrula. Given the variability and uncertainty of published *in vivo* data, and the discrepancy between batch and continuous *in vitro* culture, emphasis in the report is placed in the batch culture data (MLA 2015, Banik *et al.* 2019) and the *in vivo* data of Hutton *et al.* 2014) for characterisation of its antimethanogenic potential in livestock. As with lucerne and stylos, further *in vivo* research is recommended.

In western Australia, forages act as a break crop in cereal production and support an important sheep industry for both meat and wool. However, the proportion of grain farms including livestock in their rotation has declined in recent decades (Western Australia Department of Primary Industries and Rural Development 2025). Adapted legumes including French and yellow serradella, and subterranean clover are sown into pastures but being hard seeded they can persist in the soil for many years. Thus, seed sales are not an accurate estimation of the areas of these legumes (Clinton Revell, personal communication). French and yellow serradella, and subterranean clover while not antimethanogenic, play an important role in the wheat-sheep rotations by providing high quality forage at key times of the year. The area of these species is far in excess of that for biserrula, potentially in excess of 1 million ha in the approximate 16 million ha SW Australia agricultural zone. As a source of high CP and ME they contribute to increasing liveweight gain and thus reduce methane intensity.

Adoption of biserrula is modest, a few hundred thousand ha, compared with hundreds of thousands of hectares seeded to serradella and subterranean clover. Biserrula is relatively easy to establish and being hard seeded will persist in the soil. Thus, seed sales of around 40,000 ha per year are not a true representation of the extent of biserrula. It provides excellent forage to fill the feed gap at the end of the growing season (Western Australia Department of Primary Industries and Rural Development 2025). Anecdotally producers indicate that there is some aversion to the species and performance is often less than expected according to the nutritive value and content in the sward (Western Australia Department of Agriculture and Food 2010). Cases of photosensitisation in sheep have been reported when the plant is in excess of 40% of the diet particularly when green and actively growing. The incidence can be controlled by restricting access to the immature plants and removing affected sheep (Western Australia Department of Primary Industries and Rural Development 2025).

Plantain (*Plantago lanceolata*) is a deep-rooted perennial herb, suited to temperate growing conditions in New South Wales and Victoria. Typically it is grown as a companion species with grass, often along with chicory and other legumes (Badgery *et al.* 2023; Li *et al.* 2025). Plantain is palatable and of good nutritive value with a typical CP content of 14% DM and an ME of 10 MJ/kg DM (Agriculture Victoria 2022). Limited *in vivo* research has shown promising reductions in methane yield of between 15 and 28% when included at between 25 and 100% of the diet (Rosa *et al.* 2022; Woodmartin *et al.* 2024).

Forage brassicas for livestock include forage rape, canola (*Brassica napus*), kale (*B. oleracea*), hybrid brassicas, bulb turnips (*B. rapa*), swedes (*B. napus*), and forage radish (*Raphanus sativus*. New Zealand research suggest they are highly anti-methanogenic (Sun *et al.*

2012b). Data on the area of forage brassicas grown for livestock in Australia is not readily available but are grown in the high rainfall mixed farming zone of temperate Australia (Bell *et al.* (2020). Dual purpose crops of Canola (*B. napus*) for grazing and seed production are currently grown on over 200,000 ha (Rick Llewellyn, pers. Comm.) In temperate Australia, it is likely that the forage brassicas and bulb turnips are much less widely grown than in New Zealand. Bell *et al.* (2020) suggested that the area dedicated to brassicas had declined but there was great potential for increased adoption due to their high yield and nutritive value. They provide a valuable feed resource over summer and autumn having a CP content between 10 to 25% DM, and an ME of 10 to 14 MJ/kg DM (Bell *et al.* 2020). They have a very high proportion of soluble carbohydrate which favours a propionic digestion in the rumen. There are a number of potential toxic side effects related to the feeding of brassicas including photosensitisation and nitrate poisoning, predominantly in cattle. The prevalence of these can be reduced by avoiding grazing immature crops and a gradual introduction of naïve livestock to the crops. Typically, they are sown as pure stands and fed under controlled grazing (e.g. strip grazing) with livestock having access to companion pasture. In this way the contribution of the brassica to the diet can be controlled.

Other temperate species of potential regional importance

Ryegrass cultivars developed for high WSC content have the potential to become more prevalent in southern dairy systems High yielding and of high ME content (~14 MJ/kg DM), they have the potential to markedly increase animal performance and reduce methane yield. Currently, these cultivars are restricted in use and at the pre-adoption sage of development.

Chicory (*Cichorium intybus*) is a deep-rooted perennial herb with potential for increased adoption in temperate Australia. While it has been shown to reduce methane *in vitro* (MLA 2015; Verma *et al.* 2022; Li G 2025) a variable response was seen *in vivo* with no overall reduction (Sun *et al.* 2012a; Williams *et al.* 2016; Woodmartin *et al.* 2024). It is potentially high-yielding and high in nutritive value having a high CP content and ME value (Lee *et al.* 2015; Niderkorn *et al.* 2019). Management of the species in mixed pasture is challenging and overgrazing can result in loss of the species from the sward (Badgery *et al.* 2023).

Rhagodia is adapted to sandy soils that are marginal for cropping. Like high WSC ryegrass, it is a species currently in the pre-adoption stage but could potentially be suited to over 1 million ha of low productivity soils in the mediterranean climatic zone, where the opportunity for other species is low (Hayley Norman, pers. comm.)

4.1.6.4 Effect of grazing management

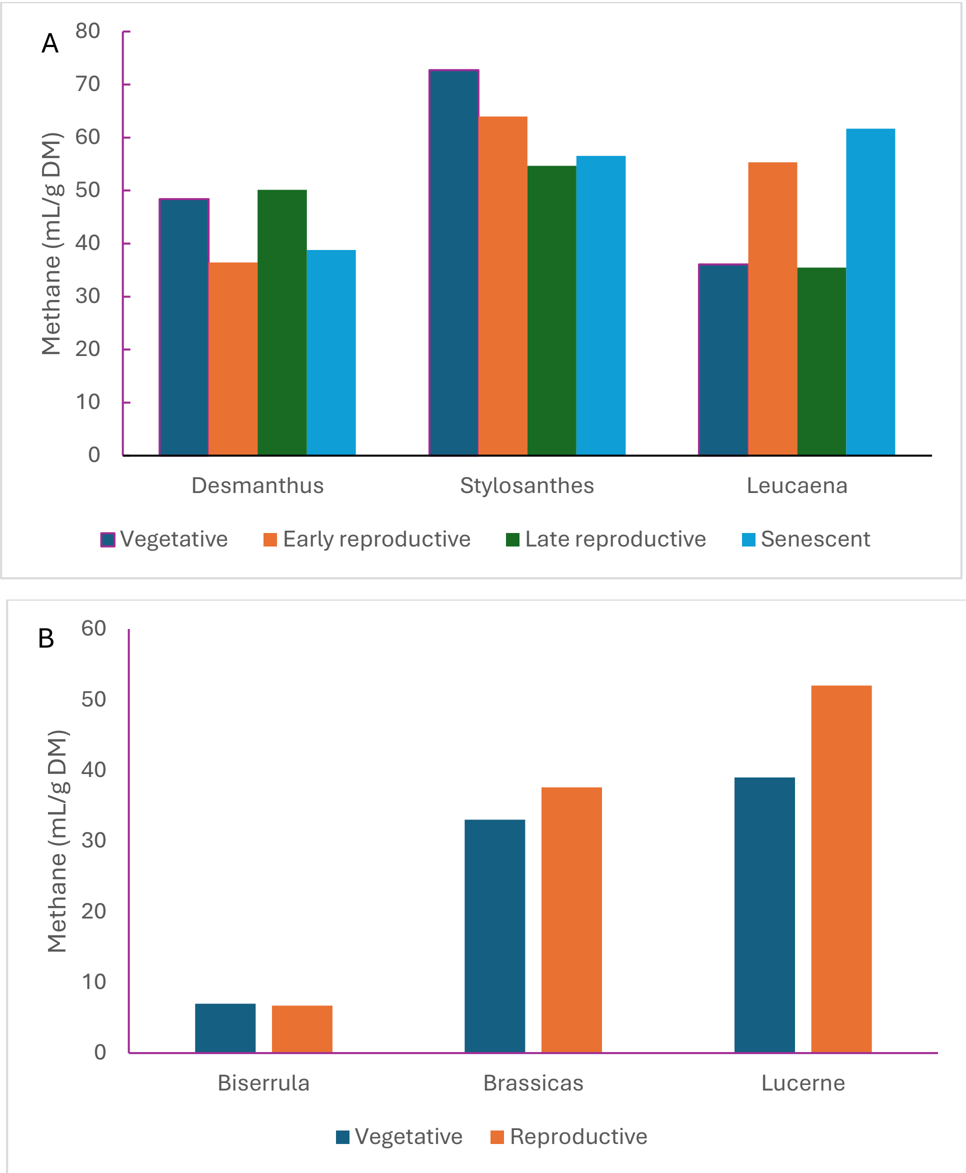
The interaction between the animal and the pasture is reciprocal in nature, with the animal influencing the amount and composition of the pasture and the pasture influencing the productivity and grazing behaviour of the animal (Charmley *et al.* 2023b). Primary among these factors are the stocking rate of the animal and utilization rate of the pasture, and the two are closely related. The grazing animal seeks to maximise nutrient intake relative to its requirements while minimizing the energy requirements and threats associated with harvesting those nutrients (Owen-Smith *et al.* 2010). The scale and heterogeneity of the pasture will influence where the animal forages and the intensity with which it will remove biomass within the feeding site or station (Rouget *et al.* 1998). The spatial and temporal variation of low-emissions species within the sward will influence the proportion of these species in the diet (Charmley 2025). Management intervention, such as rotational grazing, stocking rate and entry and exit times relative to season and feed on offer further influence diet selection. Higher stocking rates may encourage selection of less palatable species, such as tanniferous legumes, as the prehension forces of chewing grasses increase down the sward horizons (Benvenutti *et al.* 2016). The location of attractants, such as water points and supplement stations, and repellents, such as steep terrain, will influence grazing pressure and diet selection within a paddock (Tomkins and O'Reagain 2007). As paddock size is reduced and the home range becomes the entire paddock, grazing heterogeneity becomes less important.

Typically, when paddock size drops below 50 to 100 ha, depending on local soil and weather conditions, grazing behaviour is controlled less by the animal and more by management. In smaller sown paddocks, the opportunity for a more uniform species composition increases and optimising the stocking rate to achieve a desired intake of the low emissions forage can be better managed through stocking rate and grazing season. An extreme case would be grazing brassicas crops, where strip grazing allows for control over intake of the low emissions forage.

4.1.6.5 Effect of plant maturity

As plants grow and mature the concentration of the plant bioactives responsible for reducing methane emissions from livestock are likely to change. There was insufficient published information on animal experiments, however several large-scale screening studies collected *in vitro* data on methane yield from a range of species (MLA 2015; Durmic *et al.* 2017; Vandermeulen *et al.* 2018). Here, the focus is on the seven preferred species. Lucerne, brassicas, plantain, *Leucaena, Desmanthus, Stylosanthes, and* biserrula (Figure 9). Data for tropical legumes was assessed across four seasons approximating to the vegetative, early reproductive, late reproductive, and senescent growth stages. Methane production declined as maturity advanced for stylos, but was inconsistent across maturity level for *Leucaena* and *Ddesmanthus*. For temperate species, variation in methane production was higher for lucerne in the reproductive compared to vegetative growth phase. For biserrula and brassicas methane production was similar for both growth phases. However, for lucerne methane production was 40% higher in the reproductive compared to the vegetative growth phase. It is concluded that plant maturity does affect the degree of methane inhibition but the variability in response between species and across seasons makes it difficult to include plant maturity as a factor influencing methanogenesis, particularly when this is poorly defined in most *in vivo* studies. Under commercial grazing conditions plant maturity is continually changing and selective grazing habits allow both cattle and sheep to select a diet with nutritional characteristics quite different to that of the standing pasture (Charmley *et al.* 2023b). Therefore it is considered appropriate to simply use the mean mitigation value for a forage assuming it captures the typical range in plant maturity encountered by the grazing animal over time.

Figure 9. Influence of maturity on *in vitro* methane yield (mL/g DM) in tropical (A) and temperate (B) species



4.1.6.6 Effect of animal physiological status

The primary determinant of methane production in grazing animals is DM intake (Charmley *et al.* 2016; van Lingen *et al.* 2019). However, there is evidence that physiological status of the animal may also have an independent effect. Muetzel and Clark (2015) concluded that for the purposes of national emissions inventory in New Zealand, separate prediction equations were appropriate for sheep under 1 year of age and older sheep. However, the important factor was diet quality that may have indirectly influenced intake. In a cattle study Muetzel *et al.* (2024) conducted a meta-analysis of growing females, growing males, lactating females, non-growing females and non-growing males and estimated methane yield to be 24.1, 26.2, 22.1, 21.0 and 22.3 g/kg DMI, respectively. They concluded that DM intake explained most of the variation in methane production and pasture composition was not important. However, accounting for animal related parameters including LW, sex and lactation improved the prediction model. Such models are by design confounded and the authors point out that independent validation with separate datasets is important.

Based on the current state of knowledge, it is likely that factors such as age, reproductive status, and sex may influence methane production at a particular level of intake. However, these influences are small and likely independent of any antimethanogenic potential of low emissions pasture species. There is no evidence to date for example that suggests a female bovine would respond differently to a male bovine when fed a known amount of a low methane forage.

4.2 Component two: Adoptability

4.2.1 Adoption

The adoption model incorporates nine factors that influence adoption. Each was given a scale reflecting its overall impact on adoption from 0 to 3 up to 0 to 10, with the higher value indicating greater adoption. The values are given in Table 14 and a mean score calculated for each of the seven designated species. The score provides a mechanism to allow an accurate method to demonstrate the proportional variation in relative rates of adoption for the various low emissions forages.

Table 14. Adoption metrics for seven prospective species to reduce enteric methane emissions of grazing livestock. The higher the score, the more adoptable a forage.

	Economic		Agronomic		Environmental			Human		
	Cost of adoption	Access to equipment, labour, and capital	Certainty establishment/ persistence	Animal Production	Carbon benefits	Certainty of carbon benefits	Climate stability	Typology	Knowledge and access to information	Mean score
Scale	1 - 3	1 - 3	1 - 3	1 - 5	1 - 3	1 - 3	1 - 3	1 - 10	1 - 10	
Prospective species										
Lucerne	2	3	3	4	0	0	3	8	8	3.33
Brassicas	0.5	3	3	4	3	1	3	8	8	3.72
Plantain	1	3	2	4	3	1	3	8	8	3.67
Leucaena	2.5	2	2	4	3	3	2	5	6	3.28
Desmanthus	3	2	2.5	3	1	2	2	4	9	3.06
Stylos	3	3	3	3	0	0	3	4	6	2.56
Biserrula	2	2	3	3	2	1	2	6	7	3.11
Minor use species										
Ryegrass	1	3	2	4	1	0	3	8	8	3.33
Sainfoin	1	3	2	4	1	1	3	8	8	3.44
Rhagodia	2	2	2	1	3	1	3	7	5	2.89

Known linear adoption rates can be derived from a knowledge of year of introduction of a forage and the current estimated area. For dual purpose canola (Sprague *et al*. 2014), *Leucaena* (Beutel *et al*. 2018)) and *Desmanthus* (Charmley *et al*. 2025) these have been estimated to be

5.5, 3.4 and 3.1% per annum within their respective environmental zones. The mean adoption rate of 4.4% per annum was then used to adjust the individual scores for the 7 low emissions forages to individual adoption rates (Table 15). Adoption was then corrected for adoption maturity (Section 3.2.1) to produce individual annual adoption rates (Table 15). The predicted value for *Leucaena* was somewhat higher than that calculated by Kenny and Drysdale (2019) of between 0.3 and 1.2% per annum depending on the region. Nevertheless, the simplified approach was considered adequate for the purpose of including the adoption into a model forecasting future emissions from grazing livestock in that it was quantitatively sensible and accounted for individual variation in adoption of the forages.

Table 15. Method for calculating annual adoption rates over 20 years for seven prospective species to reduce enteric methane emissions of grazing livestock

	adoption score from Table 14 (%)	Annual adoption rate (%)	Years from plateau maturity	Adjusted annual adoption rate (%)
Prospective forages				
Lucerne	3.3	4.4	1	0.23
Brassicas	3.7	4.9	15	3.67
Plantain	3.7	4.8	12	2.89
Leucaena	3.3	4.3	10	2.15
Desmanthus	3.2	4.2	12	2.49
Stylos	2.8	3.6	3	0.55
Biserrula	3.1	4.1	10	2.04
Minor use forages				
Ryegrass	3.33	4.4	15	3.28
Sainfoin	3.44	4.5	10	2.26
Rhagodia	2.89	3.8	8	1.52

The process can be further explained by taking Brassicas as an example. The adoption score from Table 15 was 3.67, this being high, largely on account of the benefits in animal performance and the extent of mitigation. This value was then multiplied by the mean observed adoption of 4.45 (brassicas, *Leucaena* and *Desmanthus*) divided by their mean score of 3.39, that is 1.31. The value of 1.31 was then applied to the individual brassica mean score to derive the annual adoption rates (Table 15 data column 2). Brassicas were deemed to be 15 years away from plateau adoption making the annual adjusted adoption rate (4.48 x 15)/20 = 3.67%.

4.2.2 Animal performance benefits

Introducing a low emissions forage into a grazing system frequently results in increased individual LW gains resulting in increased LW per ha. Animal response to inclusion of low emissions forages is highly variable but had been documented. Charmley *et al.* (2025) reviewed the LWG response for *Leucaena*, *Desmanthus* and Stylos and observed a range of 40 to 70% for *Leucaena*, 0 to 10% for *Desmanthus* and 30 to 380% for stylos, the % values reflecting the values derived from the base forage which may be high or low LW gain.. Early Australian research (Morley *et al.* 1978; Wolfe *et al.* 1980) suggested a 15 to 20% increase in individual LW gain of growing cattle grazing lucerne/grass compared to grass or grass/subterranean clover pastures, while more recent review of Canadian research found a 60% increase in LWG per head and per hectare (Popp *et al.* 2000). Barry (2013) reviewed several publications on grazing brassicas showing a wide range in performance of growing lambs of between 67 and 315 g/d, values on average 20% greater than for lambs grazing grass/legume pastures. Thomas *et al.* (2021) demonstrated that inclusion of annual legumes, including biserrula, has the potential to increase diet digestibility and replace supplements when included in mediterranean grazing systems.

Despite the variability in response and widely differing production conditions for most of the prescribed species it was possible to ascribe a generalised performance response taking into account the veracity of the data and methods use in obtaining that data. For example, with temperate conditions the prospective species may simply be replacing another legume such as subterranean clover, thus minimising any performance response. For tropical diets the prospective species is typically replacing native or introduced grasses, so a higher response is expected. For modelling purposes improvement percentages in LW gain for each species were scaled to 100% inclusion. In practice the species and management of the pasture influence the grazing season of the low emissions forage and the proportion of that forage in the diet. Table 16 shows the preferred methane yield and how the improvements in performance of the prospective and minor use species are modified as used in the model.

Table 16. Mean values for methane yield (g/kg DM intake) the increase in animal LW gain (%), the percentage of the year when low emissions forages are available in pasture and their contribution to the diet when available.

	Preferred methane yield at 100% of the diet (g/kg DMI)*	Animal LWG improvement at 100% of the diet (%)*	Seasonal availability (% year)#	Contribution to the diet when available (% DMI)
Prospective species				
Lucerne	17.8	10	70	50
Brassicas	14.9	50	40	90
Plantain	9.3	10	70	30
Leucaena	18.4	50	60	30
Desmanthus	21.7	40	50	30
Stylos	15.7	60	60	40
Biserrula	16.4	50	40	60
Minor use species				
Ryegrass	18.6	10	60	90
Sainfoin	19.3	10	50	30
Rhagodia	9.7	50	12	30

*Calculated from published data where methane yield or LWG and % inclusion of the low emissions forage were known and using linear extrapolation to estimate a response assuming a diet of 100% low emissions forage. . The % increase can be very large when LWG of basal forage is very low at that time of year.

Estimates based on published literature and in consultation with specialists in the area.

4.2.3 Modelling outcomes from including low emissions species in pastures – a) prospective species

Table 17 summarises the modelled outcome of including low emissions forages into grazing systems using the adoption rates in Table 15 and the animal performance data in Table 16. Thus, increases in total AEs for each prospective species were a combination improved animal performance per ha plus increased hectares under production due to adoption. Across all species, there was a 7% increase in livestock numbers. When the effect of increased animal numbers and the reduction in methane per animal were accounted for, methane production was reduced by 2.9% per annum (Table 17).

Table 17. Changes in annual livestock production and methane emissions after adoption of seven prospective species to reduce enteric methane emissions from grazing livestock.

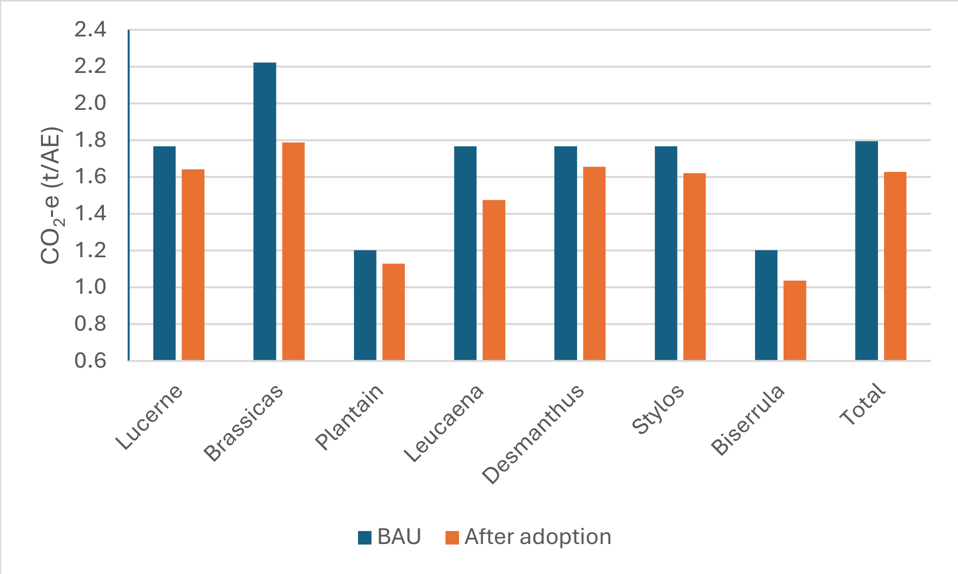
	Annual livestock numbers (,000 AE)			Annual methane production (t)		
	Business as usual	After adoption	Change (%)*	Business as usual	After adoption	Change (%)[#]
Lucerne	2,900	3,008	3.74	183,066	176,418	-3.64
Brassicas	500	608	21.5	39,666	38,826	-2.12
Plantain	94	99	5.23	4,023	3,971	-1.30
Leucaena	51	56	10.83	3,206	2,974	-7.23
Desmanthus	20	21.8	8.99	1,263	1,283	1.60
Stylos	214	246	14.60	13,527	14,255	5.38
Biserrula	119	135	13.7	5,096	5,012	-1.65
Total	**3,898**	**4,173**	**7.08**	**249,847**	**242,739**	**-2.84**

*A positive value signifies an increase in animal production

[#]A negative value signifies a reduction in emissions, a positive value signifies an increase in emissions

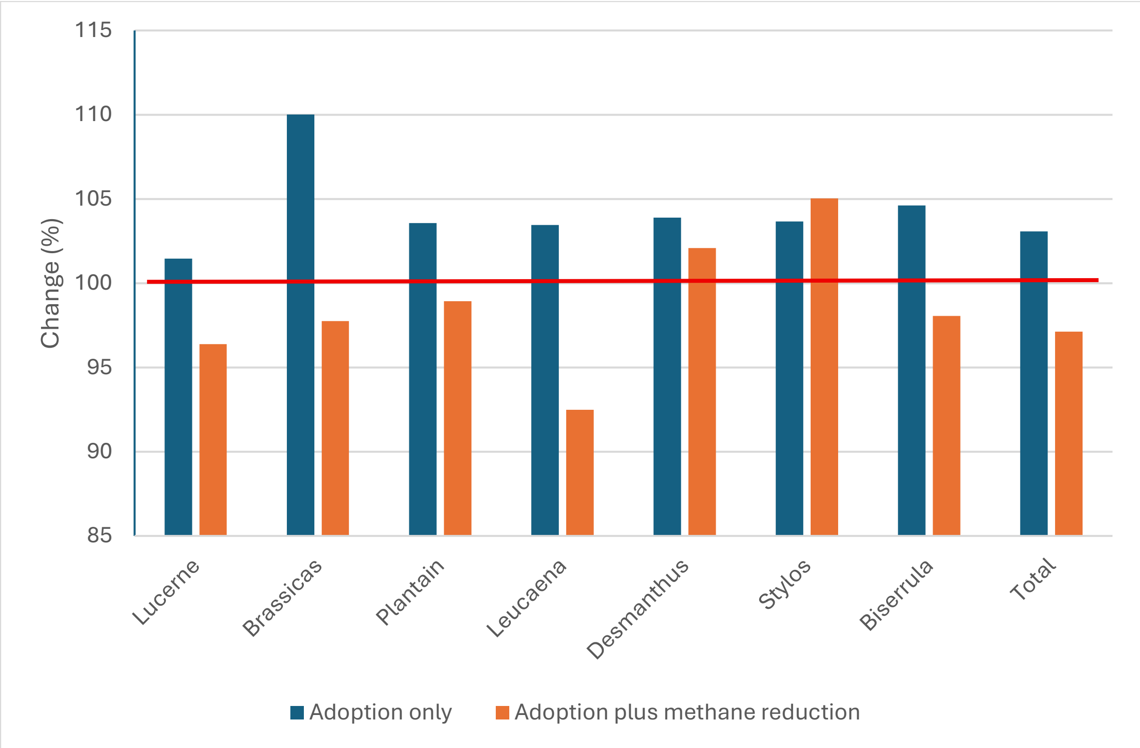
Figure 10 explores this dichotomy further, showing the intensity of methane emissions per adult equivalent expressed as CO_2 equivalents. The relative methane intensity comparing business as usual with low emissions species was proportional to the reduction in methanogenesis. The overall annual methane associated with animal product was reduced by on average140 kg/AE, an 8% reduction in emissions intensity from around 1.8 to 1.6 t/AE overall. The effect was most pronounced for brassicas and *Leucaena* dropping by approximately 20%. This highlights the importance of low emissions species eliciting both a large increase in productivity and a large reduction in methane.

Figure 10. Intensity of methane emissions (tonnes CO_2-e/adult equivalent) for business as usual (BAU) and following adoption of low emissions species.



The opposing influences of methane mitigation and increased productivity as a consequence of introducing low emissions plants into grazing systems result in complex and obscure influences on the overall methane balance. Figure 11 shows the change in methane emissions following the introduction of low emissions plants into pasture. The blue bars show the increase in methane due to increased animal productivity only, when the methane effect was “turned off”. The orange bars demonstrate the offset potential when the methane effect is “turned on”. In this way it is possible to demonstrate the influence of productivity gains as distinct from reductions in methane production. Values above the red line indicate a net increase in emissions, values below a net reduction in emissions. Brassicas represent the most extreme effects. The production response was large, owing to the high proportion of brassicas in the diet and the high nutritive value of brassicas compared to grass in the autumn/winter season. Similarly the mitigation response was large leading to a large reduction in emissions when the methane effect was included. This situation contrasts markedly to the situation for stylos, where there was relatively little influence on performance or mitigation. Clearly the response under any specific production scenario will be different, but in this example the overall effect is a 4% reduction in net methane production. For most genera the reduction in methane yield (g/kg DMI) more than offset the increase in methane production (g/d). The exceptions were for *Desmanthus* and stylos, two genera with very low or increased changes in methane yield.

Figure 11. Changes (%) in methane emissions (tonnes) compared to business as usual following the introduction of low emissions forages to pasture. Blue bars show the performance effect only, orange bars show the performance effect mitigated by the antimethanogenic potential of the low emissions forage.



In concluding this section, it is clear that overall, the abatement of emissions when including low emissions species into grazing systems was low (~4%) but variable among genera/species. This variation was attributed to the relative increase in stocking rates and reduction in emissions. Emissions intensity is related to animal productivity with productive animals typically eating more relative to LW, however these high-performance livestock can also show greater reduction in emissions intensity if much of the increase intake is from a highly antimethanogenic plant species.

4.2.3 Modelling outcomes from including low emissions species in pastures – b) minor use species.

Several other species were considered to have potential benefits, but unlikely to be widespread in their agronomic applicability. In Europe, ryegrasses of high water-soluble sugar content have been evaluated for their potential to reduce methane. Ryegrass could feasibly be grazed as a monoculture, but the suitability of cultivars to Australian conditions is limited to higher rainfall temperate areas. Limited data, with equivocal results suggests that more research in this area may yet demonstrate a worthwhile contribution to reducing methane from highly productive grass. For this reason, it is included here. Sainfoin is included here as it exhibited a medium impact on reducing methane emissions. It is not widely grown in Australia, but given its antimethanogenic potential, it could become more popular. Rhagodia, a forage shrub found predominantly in sandy soils in Western Australia and South Australia was also included as it could have potential under future climate scenarios and limited research suggest it is highly antimethanogenic. Data on methane emissions from these species are scarce and further research is warranted. However, emissions reductions estimated at 100% dietary inclusion were 10%, 7, and 54% for high water soluble carbohydrate ryegrass, Sainfoin and Rhagodia, respectively (Table 18). Ryegrass could feasibly be grazed as a monoculture, but the suitability of cultivars to Australian conditions is limited to higher rainfall temperate areas. Chicory is considered to be more widely established as a species for temperate pastures and is frequently sown in association with plantain. The additive antimethanogenic effect of these two species in animal grazing studies is warranted. *In vitro* research needs to be confirmed with *in vivo* studies to further understand its potential as a low emission species of importance.

Table 18. Changes in annual livestock production and methane emissions after adoption of three minor use species to reduce enteric methane emissions from grazing livestock.

	Annual livestock numbers (,000 AE)			Annual methane production (t)		
	Business as usual	After adoption	Change (%)*	Business as usual	After adoption	Change (%)#
Ryegrass	4.0	4.4	10.40	253	217	-14.02
Sainfoin	25.0	26.0	4.44	1,073	1,088	1.41
Rhagodia	1.2	1.3	5.66	54	53	-1.63
Total	**30.2**	**31.6**	**5.28**	**1,379**	**1,358**	**-1.53**

*A positive value signifies an increase in animal production

#A negative value signifies a reduction in emissions, a positive value signifies an increase in emissions

4.2.4 CLEM modelling for brassicas, *Desmanthus* and *Leucaena*

Brassicas

The brassicas example was relatively simple as Angus steers were introduced at an entry weight of 350 kg and remained on brassicas for almost 5 months. The large discrepancy between the diet quality of the grass mixture relative to the forage brassica resulted in a large increase in LW gain (Table 19). Two mitigation levels were compared representing low and high values as found in the literature.

Table 19. Modelling (CLEM) the effect of including forage brassicas in the diet of grazing cattle on animal performance and methane emissions at a low and high mitigation.

	Pasture	Brassicas	
	Baseline	Low mitigation	High Mitigation
DM digestibility	62.3	80.0	80.0
Crude protein (% DM)	10.2	20.0	20.0
Diet ME (MJ/kg DM)	8.85	9.75	9.75
Initial LW (kg)	350	350	350
Final LW (kg)	481	521	520
LW gain (kg/d)	0.90	1.00	1.17
DM intake			
kg/d	7.59	7.88	7.89
t/yr	1.80	1.91	1.92
% LW	1.67	1.68	1.71
Methane			
Production (g/d)	157	156	136
Yield (g/kg DMI)	20.7	20.0	17.3
Intensity (CO_2e/DMI)	0.58	0.57	0.54

Switching from a grassland- to a brassicas-based diet increased LW after 145 days grazing by approximately 40 kg. Daily methane production was similar for the grassland and low emissions brassica treatments but was reduced by 20 g/d for the high emissions scenario. Annual CO_2 emissions per head decreased from 1.6 to 1.4 t CO_2-e/year. The brassicas scenario represented the extreme example of introducing a low emissions pasture species, being very high in nutritive value, comprising a major proportion of the diet, and having a large mitigation effect. The increased ME and CP in the diet boosted LW gain. For the low mitigation scenario, the increased methane accruing from increased ME intake (calculated to be 6.7 g/d) was offset by the lower methane yield. However the high mitigation scenario more than counteracted the higher ME intake, such that both total and relative emissions were reduced. If brassicas are shown to be as effective at reducing methane as shown in New Zealand, then their use would reduce both methane production (total daily emissions) and intensity (emissions per unit animal product).

Desmanthus

Including *Desmanthus* in the pasture did not increase digestibility but increased the average CP across the year. Improving protein intake markedly increased LW gain, as heifers were highly responsive to the supply of protein for lean tissue deposition (Table 20). DM intake was estimated to be 2.4% LW, somewhat higher than what would be predicted by the Minson and McDonald (1987) equation. Reductions in methane yield were small, due to the low proportion in the diet and the low mitigation effect of *Desmanthus*. Nevertheless, methane emissions were reduced by 3% and 5% for the low and high mitigation scenarios.

Table 20. Modelling (CLEM) the effect of including *Desmanthus* in the diet of grazing cattle on animal performance and methane emissions at a low and high *Desmanthus* content of the diet.

	Pasture	*Desmanthus*	
	Baseline	Low mitigation	High Mitigation
DM digestibility	57.6	57.6	57.6
Crude protein (% DM)	6.11	7.64	8.54
Metabolizable energy (MJ/kg DM)	8.20	8.20	8.20
Initial LW (kg)	236	237	237
Final LW (kg)	469	511	511
LW gain (kg/d)	0.64	0.76	0.76
DM intake			
kg/d	9.63	9.63	9.64
t/year	3.51	3.52	3.52
% LW	2.57	2.34	2.35
Methane			
Production (g/d)	199.3	194.4	189.7
Yield (g/kg DMI)	20.7	20.2	19.7
Intensity (CO_2e/DMI)	0.58	0.57	0.55
Production (kg/yr)	72.7	71.0	69.2
Production (t CO_2 e/yr)	2.04	1.99	1.94

Leucaena

In the final scenario the objective was to model the effect on performance and methane emissions when the whole herd were given access to *Leucaena* and also when only growing cattle were given access to *Leucaena* to sale at 600 days of age. The former scenario demonstrates the relative importance of the reproductive and production herd components, while the latter is more typical of commercial practice (Table 21). The herd structure was set up to ensure 100 weaned calves every year. The grass component of the diet averages 58% digestibility, 6.1% CP and 8.2 MJ/kg DMI. *Leucaena* was given the same digestibility and ME, but CP was increased to 25%. For the modelling exercise, it was assumed that the improved nutrition of the breeder herd increased weaning rate by 10% and reduced mortality by 10%. For growing animals, the response to *Leucaena* was a 10% increase in LW gain.

Improving the nutritive value and the antimethanogenic potential of the diet for the whole herd and the planned higher weaning rate and lower mortality in the breeders increased animal output as measured in AEs by 3% and reduced annual methane output from the herd by 7%. This represents the best-case scenario with increased productivity through a higher proportion of growing cattle in the herd plus improved rates of LW gain. Even so the benefits while positive were modest. A more realistic scenario where only growing cattle receive *Leucaena* increased animal numbers by 2% but had no net effect on methane output as the reduced methane yield per unit of feed intake was offset by increased feed intake from heavier animals.

Table 21. Modelling (Excel) the effect of including *Leucaena* in the diet of grazing cattle on animal performance and methane emissions in a breeder herd (130 head) when access to *Leucaena* was given to growing and reproductive cattle or restricted to only growing cattle up to 600 days of age.

	Breeders	Cull cows	Weaners	Total
Baseline				
Total AE at year end	100	32	166	231
Methane (g/kg DMI)	20.7	20.7	20.7	20.7
Methane (t/yr)	5.53	1.93	5.21	10.77
Methane (t CO2 e/ yr)	155	54.02	145.98	302
***Leucaena* – Weaners and breeders**				
Total AE at year end	100	28	174	238
Methane (g/kg DMI)	18.6	18.6	18.6	18.6
Methane (t/yr)	4.98	1.52	5.33	10.05
Methane (t CO2 e/ yr)	139	42.55	149.16	281
***Leucaena* – weaners only**				
Total LW at year end (kg)	100	32	167	237
Methane (g/kg DMI)	20.7	20.7	18.6	19.2
Methane (t/yr)	5.53	1.93	5.00	10.68
Methane (t CO_2 e/ yr)	155	54.02	140.10	299

4.3 Component three: Feasibility of an ACCU method.

There is no likelihood of there being an approved method for low emissions forages in grazing systems under the current policy of the ACCU scheme. The recent sunsetting of two existing methodologies (Feeding Dairy Additives to Dairy cows and feeding Nitrates to Beef Cattle), the suspension of the Beef Cattle Herd Management method and the failure of the proposal from the Livestock Emissions Carbon Farming Working Group to get approval for the expression of interest (EOI) for Reducing Methane Emissions in Ruminant Livestock from Feed Additives and Forages suggest that the challenges of measurement and verification of livestock methods are of concern to the Emissions Reduction Assurance Committee (ERAC). Currently there are no livestock-related methodologies aimed at reducing enteric methane emissions. The ERAC indicated that a revised proposal of the recent feed additives and forages method EoI would be considered. The committee considered the method was not compatible with national accounting methods, therefore any reductions in methane could not be included in Australia's contribution to international emissions. The feed additives and forages method was considered unlikely to be widely applicable and likely only of value to the feedlot industry and was complex and difficult to administer. Finally, there were issues regarding the conservativeness of the method.

All of the above issues would apply to a grazed forages method, which would also have additional challenges. The low abatement potential on a per animal or area basis would reduce the financial incentive for individual producers. The issues of measurement and verification would be more complex and uncertain than for an additives method. And finally, to address the conservativeness issue, the discounting rate for earning of ACCUs would be prohibitive. In conversations with the Department of Climate Change, Energy Efficiency, and Water (DCCEEW), they strongly suggested that development of a voluntary approach to incentivise producers to reduce methane emissions would be more useful.

Despite the challenges, Gordon and Wiedemann (2023) prepared an emissions reduction framework for *Leucaena*. Their proposal was framed around knowing the numbers of cattle grazing *Leucaena*, their initial and final liveweight, the days grazing, the class of animal, and the intake of *Leucaena*. These parameters would equally apply to a more generic low emissions forages method. However, *Leucaena* was a good candidate, as it can be identified on properties from satellite, being a shrub grown in rows. For most low emissions forages their presence on a property would be difficult to identify from satellite imagery. Thus species verification would require physical ground-based assessment. The authors also highlighted several significant challenges, paramount of which was the ability to know the intake of the low emission forage. The national inventory calculates enteric methane per head from an estimation of intake and application of a relationship between intake and methane yield (Charmley *et al.* 2016). A similar approach is needed in any method that can be included in the inventory (a primary issue with the supplements EoI). There is a high degree of uncertainty in understanding intake of grazing animals (Charmley *et al.* 2023b), with factors relating to the class and performance of the animal, and species and nutritive value of the diet. For growing cattle, equations exist that relate performance to intake (e.g. Minson and McDonald 1987), but for mature animals such equations are of little use as animals may be at a stable or declining liveweight. Back-calculating intake from a knowledge of the diet quality, class, weight and weight change of the animal is perhaps the best and most universal approach in a retrospective assessment suited to a method. However, it does require a knowledge of diet nutritive value, which is typically not known.

Having acknowledged the uncertainty of estimating total DM intake, the issue of the proportion of intake that is attributed to the low emissions forage must be addressed. Using faecal NIR to estimate the % non-grass in the diet is one option. The advantage of a faecal estimate is that it avoids the problem of knowing what the animal selected in the diet. However, there are limitations as it discriminates between C3 and C4 plant species. Thus, it would be of no use in temperate systems dominated by temperate C3 grasses. Gordon and Wiedemann (2023) suggested a simpler solution using faecal NIR derived CP% and an estimate of the CP content of low CP and high CP plant species in the diet. The proportions of the low and high CP plants in the diet can then be estimated. This approach assumes that the high CP is the low emissions forage, which may apply in many situations but is not a universal solution. An alternative approach using n-alkanes or alcohols may be feasible, but the analytical requirements are excessive (Dove and Mayes 2006). A novel solution may be to use DNA fingerprinting of the forage components that could accurately discriminate all the plant species in the diet ((Malik *et al.* 2024). However, this method is novel and would require further research to develop it as a diagnostic tool.

It is concluded that the feasibility of any pasture-based method is very low under the current state of knowledge. A specific method for *Leucaena* has greater potential as it can be readily recognised in pastures, and the mitigation potential is the largest of all low-emissions species. However, as an established species with performance benefits the method may not meet the ERAC requirements for additionality and novelty.

4.3.1 Proposed framework of a potential pastures method (adapted from Gordon and Wiedemann (2023))

Prerequisites for a method likely to meet the requirements of the ERAC include a number of measurements or estimates that would be required (Table 22). For some species, particularly in southern systems, it is unlikely that any method currently exists to verify the presence and location of low emissions species apart from physically walking the paddock. However, once the presence is established the information could remain pertinent for one or several years, depending on the species. For certain other species, most notably *Leucaena*, satellite imagery would be appropriate.

An inventory of livestock grazing days, their entry and exit weights and change in LW is a prerequisite for any method and relatively easy to collect but difficult to verify and audit. As any estimate of methane requires a knowledge of DM intake, it is essential to estimate intake. This is difficult to achieve with any degree of certainty around accuracy and precision. Several methods exist based on models or equations, but different methods will produce different results. A standardised approach around back calculating intake from the class, weight and performance of the animal or group and an estimate of diet energy content is required (CSIRO 2007; MLA 2023). Metabolizable energy can be estimated from faecal NIR methods using standardised equations relating ME to digestibility. A knowledge of total DM intake can then be used to estimate methane production using the approved accounting equation.

Table 22. Proposed components of a prototype pastures methane avoidance methodology

Component	Notes	Difficulty	Precision
Verification of presence of low emissions species	Satellite imagery when practical, e.g. *Leucaena*, brassicas, possibly *Desmanthus*.	High	High
	Walking the paddock Seed sales		Low
Livestock grazing days	Inventory of livestock on and off designated area	Medium	High
Calculation of intake	Use of a recognised method (e.g. Minson and McDonald, 1997; MLA 2020 Reverse calculation from LW, LW change and diet quality. Diet quality estimated by faecal NIRS.	Low	Low
Calculation of low emissions species	For tropical conditions use of faecal NIRS to discriminate C3 from C4 species. C3 being the tropical legume	Low	Medium
	No developed method for temperate conditions	High	Unknown
Level of antimethanogenic activity	Data from literature	Low	Variable depending on species

A two-step procedure is required to sum the methane emissions from the non-antimethanogenic portion of the diet and the antimethanogenic portion of the diet. Estimating the antimethanogenic portion can be done in tropical situations from carbon isotopic ratios. Tropical grasses employ the C_4 metabolic pathway for carbohydrate assimilation while temperate grasses and legumes employ the C_3 pathway. As the isotopic ratios of carbon assimilated in the two pathways are different, isotopic analysis (or a proven NIR estimation) can be used to discriminate between the legume and the remainder of the diet. The method presupposes that the only C_3 plants in the pasture are the target low emissions species, which is often not the case. Tropical pastures are highly heterogeneous and likely will contain trees, weeds and other legumes. Methane production from the non-antimethanogenic portion of the diet is calculated according to the equation used in national carbon accounting;

MP (g/d) = DMI x NAP x 20.7

Where MP is methane production in g/d and NAP is the non-antimethanogenic proportion of the diet. The value 20.7 is the accepted methane yield (g/kg DMI) for forage-fed cattle in Australia. (Charmley *et al.* 2016). The same approach is used for the antimethanogenic portion of the diet and 20.7 is the accepted methane yield (g/kg DMI) for forage-fed cattle in Australia:

Methane production (g/d) = DMI x (1 - NAP) x (20.7 x MIP)

Where MIP is the proportional inhibition of methane taken from the literature. Total methane production is the sum of the two equations. Methane production is then converted to CO_2 equivalents using factors for global warming potential, currently 28.

Clearly there is a high degree of uncertainty in all the necessary steps. Future research is required to improve the accuracy and predictions of each necessary step. A measure-model-measure approach could be employed to improve the utility of the method. As the uncertainty is reduced the discounting factors used to assure conservativeness can be reduced. The use of novel methods such as DNA discrimination of pasture species could greatly increase the utility of the method for a wider range of production scenarios.

4.3.2 Field evaluation of the proposed method.

A recent field study over 16 months was conducted in central Queensland measuring methane production from cattle grazing buffel grass pastures with and without *Desmanthus* in the sward. The results were used to road-test the potential ACCU method (Table 23). Observed values are used for LW gain and the legume content of the diet, while predicted values for DM intake (Minson and McDonald 1987) and methane (11% reduction at 100% of diet; Table 7) were used to run the evaluation. Overall methane production (g/d) was marginally lower (5%) for the *Desmanthus* treatment largely due to high *Desmanthus* intake in the wet seasons. The method suggested that 11 kg CO_2e/yr (16 over the whole trial) were avoided on a per head basis. There was only a small increase in LW gain as a result of the inclusion of the legume. This was attributed to the similar nutritive value of buffel grass and *Desmanthus* pastures.

Table 24 compares the estimated emissions according to the method and the observed emissions as measured by the equipment measuring methane (gas emissions monitoring (GEM) units). Briefly, individual animals are attracted to the unit with a feed reward and methane is measured in the breath while the animal's head in close to the methane sensor. Over the 16 months of the study, observed reductions in emissions were higher than the estimated change in emissions according to the prototype method. This was attributed to a greater response in measured methane production to the low emissions forage (179 versus 185 g/d) compared to the model (147 versus 145 g/d for *Desmanthus* and control treatments, respectively). The 20% difference in methane production between the two methods was likely related to the estimation of DM intake. The measured approach does not rely upon DM intake to calculate methane, being recorded directly from the animal. The proposed prototype methodology used the Minson and McDonald (1987) equation and there is evidence that this equation may underestimate intake. MLA (2020) examined the equations used in the Nutrient Requirements of Domesticated Ruminants (CSIRO 2007) and adapted them for northern conditions and diets. The intake equations developed by MLA (2020) estimated DM intake to be higher than the Minson and McDonald (1987) equation over the DM intake range estimated in the current trial.

The pasture-based gas emissions monitoring method of measuring methane has been shown to accurately measure methane compared to indoor studies with cattle in open circuit respiration chambers (Hammond *et al.* 2016). However, we are not aware of other long term field studies. The Charmley (2025) study was conducted at a remote site and ongoing surveillance of cattle and GEMs was difficult, so inaccuracies cannot be ruled out.

Table 23. Methane emissions over a 16-month study using measured data for LW gain and intake, the measured amount of *Desmanthus* in the diet, and the preferred mitigation response (9%) for *Desmanthus*

	Control				Treatment			
	Wet 1	Dry	Wet 2	Overall	Wet 1	Dry	Wet 2	Overall
Season length (d)	82	76	203	441	82	76	203	441
Estimated DM intake (kg/d)	5.42	6.64	7.75	6.98	5.56	6.75	7.88	7.10
Desmanthus in the diet (%)	0	0	0	0	37	0	35	21
Measured methane production (g/d)	112	138	160	144	111	140	146	137
Estimated methane yield (g/kg DMI)	20.7	20.7	20.7	20.7	18.4	20.7	18.5	19.4
Methane intensity (g/kg LW)	0.38	0.35	0.33	0.34	0.34	0.35	0.30	0.32
Liveweight gain (kg)				317				326
Avoided emissions (kg CO_2 e)				0				15.8
Avoided emissions (kg CO_2 e/yr)				0				11.5

Table 24. Comparison of observed methane emissions from inclusion of *Desmanthus* in the pasture with predicted emissions according to the proposed methane avoidance prototype methodology

	Observed			**Predicted**		
	Grass	*Desmanthus*	Change (%)	Grass	*Desmanthus*	Change (%)
Initial LW (kg)	233	234	0.43	233	234	0.43
Final LW (kg)	550	565	2.73	550	565	2.73
Mean LW (kg)	391	399	2.04	391	399	2.04
LW gain (kg/d)	0.63	0.66	4.76	0.63	0.66	4.76
Estimated DM intake (kg/d)	7.0	7.1	1.68	7.0	7.1	1.68
Methane production (g/d)	185	179	-3.24	145	147	1.68
Methane yield (g/kg DM intake)	27.7	26.6	-3.97	20.7	20.7	0.00
Methane intensity (g/kg LW)	0.481	0.456	-5.20	0.37	0.37	0.00
Methane intensity (t CO_2-e/yr)	1.89	1.83	-3.33	1.48	1.50	1.71

4.3.3 Voluntary abatement schemes

While the opportunity for an approved emissions reduction method under the government ACCU scheme is unlikely, the opportunities under voluntary schemes, for offsetting or insetting or simply to assure market access are more promising. Tools such as SB-GAF (MLA 2021) can be employed to understand the carbon footprint of an enterprise. Currently the tool does not allow for any emission avoidance because of introducing low emission plant species into the grazing system, but this could be adapted as an ‘add-on’ based on a method like that outlined in 4.3.1. All carbon accounting methods require the establishment of a baseline year and the change in carbon balance is monitored year on year. Any net reduction in emissions that accrue can then be sold under a voluntary arrangement to offset emissions from the purchaser or held on the enterprise to demonstrate the reduction in emissions for marketing purposes, potentially for a premium price. To qualify for a method additionality must be demonstrated. That is the avoided emissions must be linked to the proposed change. In a grazing method, this would be the introduction of a low emissions species.

5. Conclusion

The literature review demonstrated the use of *in vitro* methods for initial screening of large numbers of species to determine their potential antimethanogenic potential. However, the characterisation of methane abatement in prospective species should be based on *in vivo* methods due to the consistent overestimation of methane reductions when using *in vitro* methods. For many species, the quantity of *in vivo* data is currently insufficient to provide accurate evidence of abatement potential, and further research is needed to address this deficiency. This would be crucial in assuring the industry of the benefits of adopting low emissions species and in the development of a methane avoidance method.

On the basis of *in vivo* methane data, the regional impact of a particular plant species (area, yield, persistence, etc), the animal production benefit, and adoption rate the following seven species (or genus for *Desmanthus* and *stylos*) are considered suitable for reducing methane production and/or intensity:

1) Lucerne. Widely grown and may reduce methane yield per unit of intake but reduces methane intensity per unit animal product through increased animal performance.
2) Brassicas. Potential for being more widely grown but not at scale of lucerne or *Leucaena*. Potentially large reductions in methane production and yield. A higher degree of uncertainty about the extent of methane production under Australian growing conditions.
3) Plantain. An important companion species in temperate mixed swards, known to increase animal productivity and some evidence that it reduces methane.
4) *Leucaena*. Potential for being widely grown, a high reduction in both methane production and intensity.
5) *Desmanthus*. A novel species with potential for being widely grown, a small reduction in methane yield per unit intake but can increase animal performance thus reducing methane intensity.
6) Stylos. Widely grown and reduces methane intensity per unit animal product through increased animal performance. No effect on methane yield per unit of intake.
7) Biserrula. Important in the Mediterranean zone but potential for expansion is tempered by the dominance of serradella species and subterranean clover. Large reduction in methane yield but uncertainty exists due to low number of studies.

The ongoing need for research on other species should be focussed on the options for regionally specific species combinations particularly where modes of action are complimentary. Three species were highlighted for potential further evaluation. For temperate

Australia, high WSC ryegrass and chicory offer potential benefits while in mediterranean areas, Rhagodia could be important in marginal grazing lands.

The opportunity for developing a low emissions pasture ACCU method is very low, probably non-existent. The complexity, precision and accuracy of a method are such that the ERAC would not approve a method under the current state of knowledge. Further research to ensure a method could be applied to as many species as possible and is compatible with a national accounting framework is needed. Foremost in this is the development of an accurate method to predict DM intake of grazing animals.

Of all species considered, *Leucaena* and potentially brassicas are the best candidates for inclusion in a method. They have a high rating for abatement, and for *Leucaena* there is a relatively large number of *in vivo* studies with good concurrence on abatement data. *In vivo* data on brassicas in Australia is scarce, although a recent study by Daniel Sitienei, University of New England found a 43% reduction in methane yield when sheep were fed forage brassica compared to chaff. Additional research on forage brassicas is essential to confirm this level of abatement. Both *Leucaena* and brassicas can readily be quantified on farm either through direct observation of remote sensing.

There is merit in developing low-emissions species for pastures due to their benefits on animal performance coupled with carbon accounting methods that can accommodate small reductions in methane emissions across a very large proportion of the national herd and flock. Australia's national enteric methane emissions from grazing beef cattle and sheep were 52 million tonnes of CO_2e in 2023, with 38 million tonnes from cattle and 14 million tonnes from sheep (DCCEEW, 2025). A modest 5% reduction in 50% of these livestock would avoid 1.3 million tonnes of CO_2e per year.

5.1 Key findings

- While there is a large amount of published literature on low emissions forages, understanding the antimethanogenic effects under commercial farm conditions is difficult as most data were collected under laboratory or experimental farm conditions. There is a lack of on-farm data.
- There is a wide range of plant species that have antimethanogenic activity, however only seven forages were considered to have a meaningful influence on methane emissions from grazing animals.
- The reduction in methane yield (g/kg DM intake) from diets with the seven forages varied between 0 and 25%.
- The combined influence of the seven prospective species increased animal productivity by 7% but reduced overall methane emissions by 3% and associated methane intensity (methane per unit of animal product) by 9%.
- The animal performance benefit of the seven species is the main driver for adoption by producers.
- Lower emissions intensity (i.e. emissions per unit of red meat produced) is an important consideration for the Australian red meat sector which exports much product globally.
- The opportunity for developing a method under the Australian Carbon Credit Unit (ACCU) scheme is very low, due to high complexity and low financial returns.
- The opportunity for incorporating low emissions species into grazing systems to increase animal productivity and improve the carbon balance on farm is high, through carbon farming initiatives.
- If performance of livestock on pasture is to be improved, it should be done using regionally adapted low emissions species.

5.2 Benefits to industry

The red meat industry is seen as a major contributor to global warming by society and this may be contributing to declining consumption of red meat in Australia as well as a negative sentiment towards livestock producers in general. These facts affect domestic consumption as well as access to international markets where the carbon ‘footprint’ of foods is affecting sales to lucrative markets. As other sectors reduce their carbon emissions, such as electricity generation, the share attributed to agriculture increases. It behoves the industry to be proactive. Internationally the pledge to cut global methane emissions by 30% over 10 years adds further pressure in the industry to act on enteric emissions (Global Methane Pledge 2025).

Enteric methane is a major source of greenhouse gases, contributing about 75% of all agricultural sources (DCCEEW, 2025). Therefore, the industry should pursue avenues to reduce emissions. With 95% of total methane emissions from pasture, even relatively small reductions from grazing animals can have a major impact when applied at scale across grazing systems. Full carbon accounting in agriculture remains difficult but recent developments, such as in-setting, suggest there will be solutions in the future. While the financial incentive for reducing emissions is unlikely to be significant, the societal benefit is important. Added to this the producer realizes increases in livestock production and financial returns from establishment of higher yielding and higher quality pasture species.

- The review provides realistic, unbiased information on the potential for reducing methane emissions from grazing animals.
- It provides information on the limited options for seeking revenue from avoided emissions through voluntary and government schemes.
- Enteric methane is a major source of greenhouse gases, contributing about 75% of all agricultural sources. Therefore, the industry should pursue avenues to reduce emissions.

- With 95% of total red meat sector methane emitted from pasture-fed animals, even relatively small reductions could have a noticeable impact if applied at scale across grazing systems.
- While the financial incentive for reducing emissions is unlikely to be significant or even possible, the societal benefit is significant.
- Added to this the producer realizes increases in livestock production and financial returns from establishment of higher yielding and higher quality pasture species.

6. Future research and recommendations

This review focussed on enteric methane emissions from ruminants (Table 25). However, pasture-based livestock production operates within a complex ecosystem that includes carbon dynamics in soil, plants and the atmosphere. The industry is moving from methane abatement towards the overall carbon balance of livestock production. Reports, similar to this one, on the impact of grazing ruminants on soil and plant carbon stocks and fluxes as well as emissions of other GHGs like nitrous oxide would be useful in the context of overall carbon balance. Opportunities for sequestering carbon in soils and plants and reducing nitrous oxide emissions could be explored in relation to needs and gaps in R&D and in the quantification of the impact of practice change on carbon balance.

This review sourced a large number of research trials both within Australia and internationally. *In vitro* data produced large numbers of comparisons often within the same publication which presented a useful basis for comparing different species under similar experimental conditions. However, *in vivo* trials were fewer, and fewer still compared more than one species within a single publication. Methane measurement studies using respiration chamber methods (the gold standard) are needed on lucerne, *Desmanthus*, stylos and brassicas to confirm their antimethanogenicity.

On-farm long term monitoring to assess seasonal and management effects on methane production of grazing livestock are needed to demonstrate the reduction in methane under commercial conditions. The advent of in-field monitoring units will facilitate this research. Studies should account for the effects of management, pasture species, classes of livestock and extend throughout the entire production year.

Pasture intake is central to methane production and an accurate and robust method for measuring or estimating intake is essential. Current methods are outdated and need revision or replacement. The ideal method should rely upon only easy measure variables such as animal weight and gain. Updating the current Minson and McDonald (1987) equation with modern animal data is suggested as one approach.

Extension in promoting the dual benefits of low emissions pasture species on methane reduction and animal productivity should increase adoption rates of the prospective forages nationally. Improving animal productivity from grazing systems is an important industry goal, and widespread adoption of low emissions forages can improve both animal productivity and emissions intensity.

Lucerne is the most widespread forage legume in southern Australia, yet the only *in vivo* research available was conducted under highly variable, overseas conditions. Given the small number of studies and the atypical nature of the trials, further research is needed to determine the effect of lucerne on methane yield. Methods should be compatible with best practice and compare lucerne with a widely grown control species, such as Phalaris using a dose-response design. Similar trials are not recommended for stylos due to the impracticality of harvesting and feeding stylos under animal house conditions. Field studies using GEM units would be more appropriate.

The discrepancy in methane yield from diets including brassicas in New Zealand (Sun *et al.* 2015) and Australia (Williams *et al* 2016) is of concern, particularly as no effects were observed in Australian *in vitro* studies (MLA 2015). Further *in vivo* research is required as described for lucerne. Of particular interest would be discerning the methane response from bulb versus leafy cultivars.

The complementarity of different antimethanogenic compounds to provide additive effects on methane reduction has not been studied in Australia using animals. Studies could include forages that have different modes of action such as tannins in sainfoin and saponins in lucerne. Alternatively, the combination of supplements such as Bovaer or *Asparagopsis* with *Leucaena* could result in a significant and sustained reduction in methane emissions of grazing cattle.

The lack of on-farm trials is of concern. The study by Charmley (2025) highlighted challenges associated with long-term measurements in the field and noted the discrepancy between estimated and observed data. With the widespread use of GEM units, it is now practical to gather on-farm data, and more studies are required with the six prospective species. Emphasis should be placed in lucerne, *Leucaena, Desmanthus,* biserrula and stylos, given their agronomic importance.

Table 25. Recommendations for future research.

Research study	Recommendation
Similar reviews on carbon balance	Similarly styled reviews on the impact and potential mitigation of the impact of grazing ruminants on soil carbon and emissions of other GHGs
In vitro screening for prospective species	Reduce emphasis on *in vitro* studies of this nature, it is unlikely further low-emissions species remain to be found
Estimating/measuring low-emissions species in the diet	Techniques to measure or estimate individual low emission species in the diet of grazing livestock is urgently required if GHG avoidance methods are to be developed for the grazing industry
New method for estimating intake of grazing animals	The current Minson and McDonald equation underestimates intake, alternative methods must rely on easy to measure variables (e.g. LW and LWG, body imaging).
Methane measurement trials on lucerne	*In vitro* studies indicate lucerne may have a small antimethanogenic effect due to the presence of saponins. *In vivo* trials are required to confirm this supposition
Methane measurement trials on brassicas	New Zealand studies suggest brassicas cause significant reductions in methane yield. Studies under Australian conditions are required to confirm this
Methane measurement trials with combinations	These should include mixes of low emissions forages as well as low emissions forages with supplements such as Bovaer
On-farm season-long studies on lucerne, *Leucaena, Desmanthus,* biserrula and stylos	As these species are most likely to feature in a potential GHG avoidance method, studies under commercial conditions are essential to reduce the uncertainty around the quantum of avoided emissions.
Minor-use tropical legumes	Calliandra, lablab and siratro deserve further research with *in vivo* studies to confirm limited evidence that they may reduce methane emissions.
Extension and adoption	Extension in promoting the dual benefits of low emissions pasture species on methane reduction and animal productivity should increase adoption rates of the prospective forages nationally. Improving animal productivity from grazing systems is an important industry goal, and widespread adoption of low emissions forages can improve both animal productivity and emissions intensity.

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8. Appendices

Appendix 8.1 References used for Tables 3 and 4 and Figures 5, 6, and 7.

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Appendix 8.2. References used for Tables 5, 6, and 7.

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Appendix 8.3. Link to data from publications on *in vitro* methane emissions

https://www.mla.com.au/globalassets/mla-corporate/research-and-development/documents/in-vitro-dataset-for-mla.xlsx

Appendix 8.4. Link to data from publications on *in vivo* methane emissions

https://www.mla.com.au/globalassets/mla-corporate/research-and-development/documents/in-vivo-dataset-for-mla.xlsx

Appendix 8.5. Link to calculations for estimating adoption and national methane emissions from the seven prospective and 3 minor use low emissions forage.

https://www.mla.com.au/globalassets/mla-corporate/research-and-development/documents/calculating--national-impact.xlsx