SPECIAL ISSUE | REVIEW
https://doi.org/10.1071/CP22299
CROP & PASTURE SCIENCE

Reducing enteric methane of ruminants in Australian grazing systems – a review of the role for temperate legumes and herbs

Warwick Badgery[A,*], Guangdi Li[B], Aaron Simmons[C], Jennifer Wood[D], Rowan Smith[E], David Peck[F], Lachlan Ingram[G], Zoey Durmic[H], Annette Cowie[I], Alan Humphries[F], Peter Hutton[H], Emma Winslow[J], Phil Vercoe[H] and Richard Eckard[K]

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

*Correspondence to:
Warwick Badgery
NSW Department of Primary Industries, Orange Agricultural Institute, 1447 Forest Road, Orange, NSW 2800, Australia
Email: Warwick.badgery@dpi.nsw.gov.au

Handling Editor:
Brendan Cullen

Received: 31 August 2022
Accepted: 23 January 2023
Published: 20 February 2023

Cite this:
Badgery W *et al.* (2023)
Crop & Pasture Science, **74**(7–8), 661–679.
doi:10.1071/CP22299

© 2023 The Author(s) (or their employer(s)). Published by CSIRO Publishing.
This is an open access article distributed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND).

OPEN ACCESS

ABSTRACT

In Australia, 71% of agricultural greenhouse gas (GHG) emissions are enteric methane (CH_4), mostly produced by grazing sheep and cattle. Temperate low CH_4 yielding legumes and herbs can mitigate enteric CH_4 production, but system-level GHG emissions need to be considered. The aims of the study were to: (1) devise a framework to assess GHG reductions when introducing low CH_4 yielding species; (2) assess mechanisms of CH_4 reduction in temperate legume and herb species for Australia; (3) use a case study to demonstrate expected changes to system-level GHG emissions with the introduction of low CH_4 yielding legumes; and (4) identify knowledge gaps and research priorities. Results demonstrate lowering emissions intensity (kg CO_2-equivalent/kg product) is crucial to mitigate GHG emissions, but livestock productivity is also important. Several pasture species have anti-methanogenic properties, but responses often vary considerably. Of the species investigated biserrula (*Biserrula pelecinus*) has great potential to reduce enteric CH_4 emissions, but in a case study its emission intensity was similar to subterranean clover (*Trifolium subterraneum*) but higher than lucerne (*Medicago sativa*). We conclude that there are temperate legumes and herbs with anti-methanogenic properties, and/or high productivity that could reduce total CH_4 emissions and emissions intensity of ruminant livestock production. There is also great diversity in some plant genotypes that can be exploited, and this will be aided by more detailed understanding of plant secondary compounds associated with CH_4 reduction. This review suggests an opportunity to formulate pasture species mixtures to achieve reduced CH_4 emissions with greater or equal livestock production.

Keywords: bioactive plants, grazing systems, greenhouse gas reduction, herbs, legumes, livestock production, methane emissions, temperate pastures.

Introduction

Australia is a signatory to the Paris Agreement, which aims to limit global warming to no more than 2°C above pre-industrial levels. To meet this goal, there is an imperative to rapidly reduce global greenhouse gas (GHG) emissions. While reductions in GHG emissions are needed from most sectors, limiting global warming to below 2°C cannot be achieved without reducing emissions from the agricultural sector (Reisinger *et al.* 2021). In Australia, agriculture produces about 76.1 Mt carbon dioxide equivalents (CO_2-e) annually, which is about 15% of the national emissions (Commonwealth of Australia 2022). Approximately 71% of agricultural emissions are methane (CH_4) emitted from livestock, with enteric CH_4 emissions being the dominant source, equating to 48.2 Mt of CO_2-e emitted annually (DISER 2021). While there are other emissions sources in agricultural systems [e.g. nitrous oxide (N_2O) from soil], these sources make significantly lower contributions to the total GHG emissions of the agriculture sector. When the targets for GHG emissions reductions set by most multinational supply chain companies are considered, in conjunction with the fact that around 70% of Australian agricultural product is exported, reducing GHG emissions from agriculture has also become an imperative to maintain market access. The relatively high proportion of GHG emissions that are attributed to livestock means significant research and adoption is needed to reduce GHG emissions from grazing animals to maintain market access.

There is potential to reduce enteric CH_4 through use of several classes of feed additives, including oils, nitrates, phytochemicals, essential oils and methane inhibitors (Almeida *et al.* 2021). While macroalgae, such as red seaweed (*Asparagopsis taxiformis* and *Asparagopsis armata*), and 3-nitrooxypropanol (3-NOP) are considered to have the greatest potential (Black *et al.* 2021) there are also potential limitations. In grazing systems, effective methods for delivery of the required dose and economic feasibility are yet to be determined, while some animal welfare concerns have also been identified for macroalgae (Li *et al.* 2018). These technologies can be implemented in intensive feeding systems, but these barriers must be overcome before they can be used in extensive grazing systems.

In Australia, sheep and beef production is mostly based on grazing, with ~96% of animals grazed on pasture (MLA 2022). Any feed additives with the potential to reduce enteric CH_4 emissions must be provided to grazing livestock to have an industry-wide impact. Of the 416 million ha of Australian land that is grazed by sheep and cattle, approximately 71 million ha is improved pasture (DAWE 2016), including 23 million ha of sown pasture in the temperate pasture zone (Badgery *et al.* 2015). While it is difficult to determine the exact numbers of livestock that are supported by sown pastures in the temperate region, there are ~9.4 million cattle or 40% of the herd and 58.4 million sheep or 92% of the flock grazed in this region (MLA 2022), supporting a significant proportion of Australia's red meat and wool production. New solutions to mitigate enteric CH_4 emissions must target these extensive grazing systems.

Pasture species, including a large number of legumes, grasses and herbs, can produce bioactive compounds that reduce enteric CH_4 emissions (Beauchemin *et al.* 2008; Eckard *et al.* 2010; Banik *et al.* 2013*a*). The main mechanism by which these forages reduce enteric CH_4 is through their expression of specific plant secondary compounds (PSC), however they can also reduce enteric CH_4 emissions intensity, the amount of emissions per unit of product (i.e. meat, milk, wool), by improving the overall nutritional value of pastures. The key anti-methanogenic bioactive compounds in these forages include fats and oils (Moate *et al.* 2016), phenolic compounds like condensed tannins (CT; Grainger *et al.* 2009), saponins (Eckard *et al.* 2010) as well as nitrates and sulfates (Beauchemin *et al.* 2020). The temperate grazing systems of Australia generally have mixed pastures, containing legumes and grass species, and new options will have to be adapted to these systems.

The anti-methanogenic properties of pasture species have been largely identified through *in vitro* fermentation and pen feeding studies. It is a significant step from these laboratory and controlled environment studies to validating the efficacy of anti-methanogenic pasture species in delivering abatement of GHGs at the farm level. The quality and productivity characteristics of the forages, together with animal interactions and selective grazing, all impact dry matter intake (DMI) of animals thereby affecting enteric CH_4 emissions (Charmley *et al.* 2016), animal production and ultimately GHG emissions. Furthermore, the agronomic suitability and persistence in a mixed pasture need to be compared to currently recommended species at a regional level. Any changes in plant characteristics, productivity and persistence can flow through to changes to soil properties and influence N_2O emissions and soil carbon (C) levels. To deliver GHG abatement, animal productivity should be maintained while net emissions are reduced. Farm system-level assessment is needed to determine GHG mitigation potential from introducing these species.

This review: (1) presents a framework to assess legumes and herbs with anti-methanogenic properties, for effectiveness in reducing GHG emissions at a system level when introduced into temperate pasture systems in southern Australia; (2) uses existing literature to short-list potential legume and herb species for temperate pasture systems; (3) provides a case study to demonstrate expected changes to system level emissions via replacement of subterranean clover (*Trifolium subterraneum*) with the introduction of biserrula (*Biserrula pelecinus*), a low methane legume, or lucerne (*Medicago sativa*), a perennial legume with high productivity; and (4) identifies knowledge gaps and research priorities.

Framework for assessing GHG reduction potential of pasture species

Many forage species have been identified as having anti-methanogenic properties, but not all of these will result in reduced GHG emissions for a livestock system. There are a number of other lenses that a species must be assessed through, to ensure GHG abatement occurs. A framework to determine GHG emission reduction potential of pasture species should include: (1) broad screening of pasture species and cultivars, generally screening for plant secondary compounds (PSC) to rank their relative enteric CH_4 reduction potential (once *in vivo* results or validated *in vitro* fermentation methods have been used to identify associations with CH_4 reduction); (2) an assessment of their agronomic suitability and productivity for a target region and grazing system; (3) validation of animal production and enteric CH_4 reduction under grazing; and (4) an assessment of changes in all GHGs, and the net GHG balance, at a systems level (Fig. 1). This framework would operate as a funnel with broad, rapid and low-cost screening at the top (assuming the associations between PSC and CH_4 reduction are already

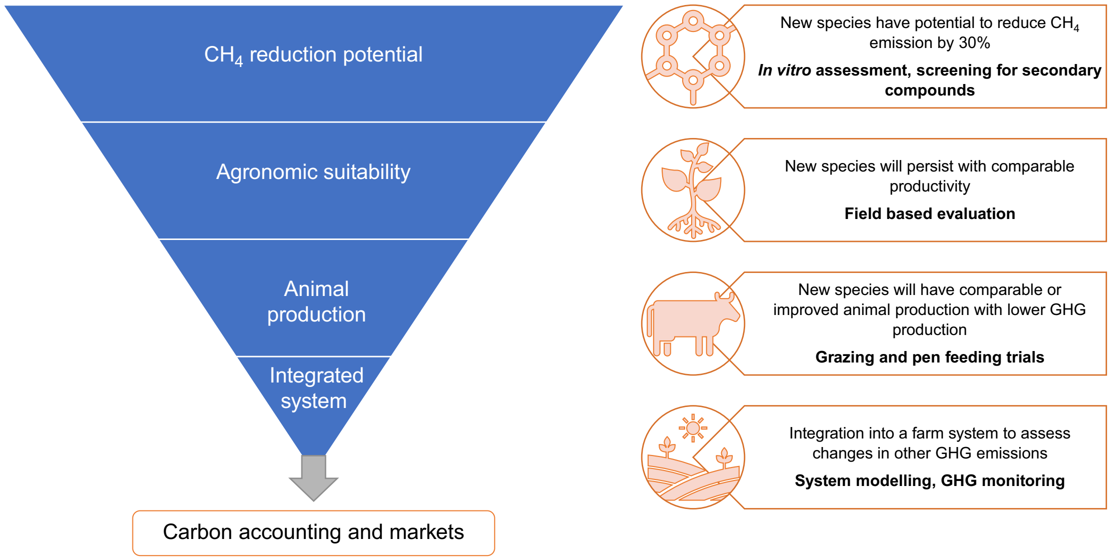

Fig. 1. Framework to assess anti-methanogenic potential of pasture species. Generally, the evaluation of species at the top of the funnel has high species throughput, shorter duration and lower cost. Further down the funnel the number of species decreases, the duration can be longer, the cost of evaluation higher and the complexity increases.

established), through to more detailed, time consuming and costly *in vivo* assessments on fewer, more promising species and cultivars at the bottom. A goal is to shorten the time for species to pass through this funnel. Additional opportunities exist to develop even more rapid screening technologies to detect specific PSC associated with CH_4 reduction in pastures once these relationships are established. Potential technologies could include near-infrared spectroscopy, hyperspectral imaging or rapid colorimetric assay approaches. Many species have been proven to have potential for GHG mitigation in temperate grazing systems of Australia at a number of these levels as detailed in following sections.

Description of compounds and mechanisms of methane suppression

Plant secondary compounds or secondary metabolites of pastures, such as tannins, saponins, and other polyphenolic compounds, have potential to reduce CH_4 emissions in ruminant livestock (Waghorn 2008; Ku-Vera *et al.* 2020; Waters *et al.* 2020; Tava *et al.* 2022). The role of the major PSC are described below.

Tannins

Tannins are a subset of compounds belonging to the polyphenolic compound group, which is ubiquitous within the plant kingdom. Polyphenolics are plant secondary metabolites that range from simple phenolics right through to high molecular weight polymeric compounds. Tannins are highly polymerised and hydroxylated polyphenol compounds (molecular weight ~500–3000) and they have been historically studied as anti-nutritional factors in relation to animal nutrition (Kumar and Singh 1984) and for bloat prevention (Lees *et al.* 1981; Min *et al.* 2005; Mueller-Harvey 2006). Tannins are a chemically diverse group that comprise two main classes; condensed tannins CT (having a flavan-3-ol base unit and synthesised via the phenylpropanoid pathway) and hydrolysable tannins (HT; characterised as having a gallic acid base unit and synthesised via the shikimate pathway) (Mora *et al.* 2022).

Condensed tannins, also known as polymeric proanthocyanidins, have received the most attention with regards to CH_4 mitigation. Reviews have shown that pastures containing CT can reduce CH_4 production (Aboagye and Beauchemin 2019; Min *et al.* 2020). However, because CT can form complexes with both proteins and fibre, this can reduce protein digestibility, ruminal fermentation and may reduce the absorption of nutrients, thereby decreasing livestock productivity. Reduced protein availability will lower urine N excretion, and any reduction in fermentation will decrease H_2 production and therefore enteric CH_4 (Min *et al.* 2020). The potential reduction in livestock productivity of a high CT diet will need to be balanced with the CH_4 reduction goal and other reported benefits of CT including reduced gut parasites, and improved milk production, wool growth, immune responses and reproduction (Waghorn 2008; Min *et al.* 2020). In addition, CT may affect meat and milk quality as they can inhibit the biohydrogenation of unsaturated fatty acids (Vasta *et al.* 2019).

Hydrolysable tannins have received little attention with respect to their potential for reducing enteric CH_4. Historically, HT are known for their potential toxicity to livestock (McSweeney *et al.* 1988; Waghorn 2008). However, at low levels HT show some potential for reducing CH_4 emissions via protein-binding (Jayanegara *et al.* 2015) or directly interacting with rumen microbiota without affecting fibre digestion (Vasta *et al.* 2019). Jayanegara *et al.* (2010) found that HT have a more direct effect on either the protozoa (responsible for H_2 production) or the methanogens (responsible for CH_4 production), inhibiting their growth or activity, without reducing fibre fermentation. Similarly, HT may affect meat and milk quality as well but to a lesser degree than CT (Vasta *et al.* 2019). A greater understanding of the tannin content, particularly HT, and investigation into the range and composition of phenolic compounds in temperate pasture species will help identify opportunities for alternate species and cultivars that have greater CH_4 reduction potential.

Saponins

Saponins are another class of secondary metabolites synthesised by, and present within, some plant species. Saponins are a heterogeneous subclass of terpenoid compounds with a base structure of either triterpene, steroid, steroidal alkaloid or an acyclic C chain, often occurring as glycosides (Jayanegara *et al.* 2010). Dicotyledonous plant species commonly accumulate triterpenoid-type saponins, whereas plants like Asparagaceae generally synthesise steroidal-type saponins. Grasses often have no saponins, although oats (*Avena sativa*) are an exception, accumulating both steroidal and triterpenoid saponins (Moses *et al.* 2014). Historically, some saponins are known to be toxic, and some saponins can taste bitter thus deterring animal grazing, especially in mixed pastures (Lei *et al.* 2019).

Saponin-rich non-pasture plants, like tea (*Camellia sinensis*), yucca (*Yucca schidigera*) and *Quillaja saponaria* have been shown to decrease CH_4 emissions *in vitro* (Jayanegara *et al.* 2014). The CH_4 reductions of lucerne and biserrula are thought to be due to their saponin content (Malik and Singhal 2009; Ghamkhar *et al.* 2018; Kozłowska *et al.* 2021). Saponins have been measured in all *Medicago* species studied, but the amount and type of saponin present vary within and between *Medicago* species (Tava and Pecetti 2012; Szumacher-Strabel *et al.* 2019) and affect their biological activity (Tava and Pecetti 2012; Kozłowska *et al.* 2021). Kozłowska *et al.* (2021) found that two of four saponins extracted from lucerne leaves reduced CH_4 production but the effectiveness of saponins depends on their source, type and concentration. Szumacher-Strabel *et al.* (2019) reported that total saponin concentration can increase 1.7–4.4 times in ensiled lucerne compared to fresh lucerne, with the magnitude cultivar dependent. Ghamkhar *et al.* (2018) found 47 metabolites associated with low CH_4 production in biserrula. A species closely related to the genus *Biserrula* is *Astragalus*, the largest species in the Fabaceae family, which contains saponins that potentially could lower CH_4 (Ionkova *et al.* 2014). The perennial legume Sulla (*Hedysarum coronarium*) also contains saponins (Tava *et al.* 2022). Knowledge of saponins in pasture species is limited, but the literature suggests that further exploration of saponin content and types is warranted in the search for low CH_4 pastures.

Methane suppression by saponin is thought to be related to inhibition of rumen ciliate protozoa responsible for production of H_2, as a precursor for methanogens to convert into CH_4. Thus, CH_4 production decreases as fermentation is shifted in favour of propionate production (Patra *et al.* 2017; Ku-Vera *et al.* 2020). However, despite decreasing protozoal numbers by 40–50%, Jayanegara *et al.* (2010) indicated a weak association between anti-protozoal activity of saponins and methanogenesis. Thus, any bioactive properties and enteric CH_4 mitigating effects will be influenced by the saponin source, the chemical structure and concentration present in feed (Jayanegara *et al.* 2014). Additional bioactive effects associated with saponins include anthelmintic properties *in vitro* (Maestrini *et al.* 2020) and protection against aphids (Goławska *et al.* 2012).

Saponins may contribute to stable foam in the rumen that can cause bloat. However, Majak *et al.* (1980) compared bloat incidence on high saponin and low saponin near-isogenic strains of lucerne and concluded that saponins did not contribute to the occurrence of bloat. Nevertheless, it would be advisable to exercise duty of care and investigate potential bloat risk for pasture species with increased levels of saponins.

Other polyphenolic compounds

Other classes of phenolic compounds have been largely ignored in livestock research, but they also have the potential to contribute to CH_4 mitigation. The five main groups of non-tannin polyphenols are phenolic acids, flavonoids (e.g. anthocyanins, flavanols, flavanones, flavonols, flavonones, and isoflavones), xanthones, lignans and stilbenes. Banik *et al.* (2016) found three bioactive fractions from biserrula that reduced CH_4 production by more than 50%, with two of the fractions possibly containing flavonoid glycosides. Jayanegara *et al.* (2010) demonstrated the ability of phenolic acids (cinnamic, caffeic, *p*-coumaric and ferulic acids) to decrease CH_4 production significantly during *in vitro* rumen fermentation. In addition, the molecular structure of phenolic compounds appears to be important, with higher numbers of hydroxyl groups eliciting stronger methane inhibition (Jayanegara *et al.* 2010). In addition, non-tannin phenolic compounds are less likely to decrease the availability of proteins and other nutrients necessary for livestock productivity and may confer additional bioactive effects associated with phenolic compound consumption in humans. For example, non-tannin phenolic compounds can provide antioxidant, antibacterial, antifungal, anti-inflammatory, anti-carcinogenic, anti-diabetic, antihypertensive, antihyperlipidaemic, hepatoprotective, antispasmodic, oestrogenic, and neuroprotective benefits (Makkar 2003; Siah *et al.* 2012; Durazzo *et al.* 2019).

Pasture species with CH_4 emission reduction potential

There have been several broad-based assessments of the potential of pasture species to reduce enteric CH_4 production in Australia (e.g. Banik *et al.* 2013*a*) and internationally (e.g. Aboagye and Beauchemin 2019). These assessments have helped to identify species that have the greatest potential to reduce enteric CH_4 in grazing livestock and identify the mechanisms for CH_4 emission reduction. The most promising legume and herb species from a CH_4 reduction and production perspective for temperate environments in Australia are listed in Table 1. The range of CH_4 reduction has been listed based on published data from *in vitro*, pen and grazing studies. The PSC potentially associated with anti-methanogenic properties for each species are also listed; as is the productivity, persistence and general agronomic suitability.

Perennial legumes

The inclusion of perennial legumes in mixed pastures can improve nutritional quality of feed, fix nitrogen, increase ground cover, and reduce variability in pasture production. The two major perennial legumes grown in Australia are lucerne and white clover (*Trifolium repens*) (Nichols *et al.* 2012), but these species are currently not recognised for having anti-methanogenic properties and new low CH_4 cultivars would need to be developed.

Lotus

The *Lotus* species have great potential to reduce enteric CH_4 emissions. Across numerous studies a 38% reduction in enteric CH_4 emissions has been reported when compared to common pasture species like perennial ryegrass (*Lolium perenne*), although variability has been considerable (Table 1). Condensed tannins are believed to be the main PSC responsible for reducing CH_4 in *Lotus*. By comparing lotus (*Lotus pedunculatus*) fed to young rams with and without polyethylene glycol to bind with and remove the effects of CT, Waghorn *et al.* (2002) found CT responsible for 16% of the reduction in CH_4 production. This study reported that CH_4 production from lotus (11.5 g/kg DMI) was much lower than that from perennial ryegrass–white clover pasture (25.7 g/kg DMI) indicating other mechanisms are also involved.

Three *Lotus* species have been grown in Australia, namely lotus (*Lotus uliginosus* syn. *L. pedunculatus*), birdsfoot trefoil (*Lotus corniculatus*) and narrowleaf trefoil (*Lotus tenuis*), with *L. uliginosus* by far the most widely grown. Harris *et al.* (1993) reported that 5500 ha of cv. Grasslands Maku (Armstrong 1974) were sown in the coastal regions of eastern Australia for beef and dairy production in 1990, though Blumenthal and McGraw (1999) later reported the combined total area sown to *Lotus* sp. in Australia could be as much as 100 000 ha. However, there are currently no *Lotus* cultivars being grown for certified seed (Australian Seeds Authority Ltd. 2021*a*, 2021*b*), nor are there any eligible for seed certification in Australia (Australian Seeds Authority Ltd. 2021*c*), which is a barrier to increased adoption of *Lotus* sp.

L. uliginosus, *L. tenuis* and *L. corniculatus* have proven to be waterlogging tolerant (Real *et al.* 2008), though only *L. tenuis* and *L. corniculatus* tolerate salinity while *L. uliginosus* tolerates aluminium (Schachtman and Kelman 1991). Drought has proven a significant barrier to lotus persistence (Ayres *et al.* 2006*a*). In New South Wales, Grasslands Maku outperformed white clover at temperate sites where summer moisture deficits are relatively short; the reverse was the case in sub-tropical sites (Blumenthal *et al.* 1999). This is consistent with early reports by Armstrong (1974) that Maku would outperform white clover in soils that are moist, low pH, or low in fertility. Further studies by Ayres *et al.* (2006*b*) identified that *L. uliginosus* was best suited to the high rainfall zone (>1000 mm average annual rainfall (AAR)), whereas *L. corniculatus* was better suited to the low fertility, low pH regions of 650–1000 mm AAR. This is consistent with the suggestion of Dear *et al.* (2003) that *Lotus* sp. have potential on waterlogged and acidic soils and with current advice (NSW DPI 2017). Surveys of growers and agronomists indicated that research was required into establishment, dry matter (DM) production, quality, persistence and seed production (Harris *et al.* 1993). Barriers to adoption of *L. corniculatus* in New Zealand were listed by Chapman *et al.* (1990) as being associated with establishment (appropriate and successful inoculation with rhizobia), and inappropriate grazing management. Under Australian conditions *L. corniculatus* has not persisted well compared to other adapted species (Hayes *et al.* 2023).

Sainfoin

Sainfoin (*Onobrychis viciifolia*) reduced enteric CH_4 production by 13% on average, with reductions as high as 48% (Table 1) mainly when compared to ryegrass pasture. When fed to beef cattle sainfoin did not reduce CH_4 emission compared to lucerne after correction for intake (26.1 vs 25.7 g/kg DMI) (Chung *et al.* 2013). Sainfoin accessions collected from different environments varied substantially in terms of *in vitro* CH_4 production, indicating the potential for selection of new low-CH_4-yielding cultivars (Hatew *et al.* 2015).

Although sainfoin has been successfully grown in north America and northern Europe (Rumball 1982; Dear *et al.* 2003), it has not been a commercial success in Australia since cv. Othello was first introduced in 1980 (Oram 1990; Nichols *et al.* 2012). Evaluations in New Zealand led by Rumball (1982) demonstrated it had a limited role, as it

Table 1. Temperate pasture species and their potential to reduce methane emissions.

Functional group	Pasture species/group	Δ CH_4%, (Range, %)	Potential PSC	Minimum rainfall (mm)[A]	Soil conditions it will tolerate and/or grow well[A]	Production	Persistence	Livestock
Perennial legumes	*Lotus* spp. (a) Big trefoil (b) Birdsfoot trefoil	**−38,** (−64 to 2)[1–6]	CT[1, 27]	(a) 1000 (b) 650–750	(a) Acid soils; waterlogging (b) Moderately acidic soils	**	**	(a) Low bloat risk (b) Non-bloating
	Lucerne	**−4**/+6[B] (−27 to 20/126)[1, 6–16]	Phen, Sap[27]	375–400	Moderately acid to moderately neutral soils, well-drained	*****	****	Bloat risk
	Perennial clovers (a) Red clover (b) White clover	**−2,** (−31 to 42)[1, 2, 5, 6, 17–20]	T, Phen[1, 27]	(a) 700 (b) 750	(a) Well-drained; slightly acid to neutral soils (b) Slightly acid to neutral soils	** ***	** ***	(a) High oestrogen (b) Bloat risk
	Sainfoin	**−13,** (−48 to 2)[7–9, 14, 21]	CT, Phen[27]	350	Alkaline, sandy soils	**	**	Non-bloating
	Sulla	**−32,** (–)[6]	T, Sap[27]	400–800	Neutral to alkaline	***	*	Non-bloating
Annual legumes	Annual clovers (a) Arrowleaf clover (b) Bladder clover (c) Subterranean clover	**1,** (−28 to 49)[1, 13, 22]	T, Phen[1, 27]	a) 400–500 b) 350–800 c) 375–600	Slightly/moderately acidic to neutral. Bladder and sub-clover prefer well-drained soil	**** *** ****	** ** *****	(a) Bloat risk (b) Bloat risk (c) Older cultivars can have high oestrogen
	Biserrula	**−77,** (–)[1]	Phen[28]	400–525	Acid soils	****	*****	Photosensitisation risk
	Burr medic	**+11,** (–)[1]	Phen, Sap[27]	300–700	Mildly acidic soil	**	****	No known issues
	Serradella (a) French serradella (b) Yellow serradella	**+7,** (2 to 12)[1]	Phen[28]	a) 375–475 b) 400–450	(a) Well-drained; Acid soils; high Al (b) Sandy, acidic well-drained soils. High Al	****	****	No known issues
Perennial herbs	Chicory	**−11,** (−37 to 2)[2, 6, 22–26]	CT, Phen, Sap[29, 30]	600–750	Acid soil; good fertility	****	***	No known issues
	Plantain	**−18,** (−21 to −14)[2, 22]	CT, Sap[31]	500–650 mm	Low fertility soils	***	***	No known issues

The Δ CH_4 production is the percentage change relative to the control, typically perennial ryegrass, of the species of interest using *in vitro*, respiration chambers, sulfur hexafluoride tracer (SF6) or anaerobic digestor on freshly harvested or grazed materials. The average of all studies for each pasture species/grouping is shown in bold. Negative values represent a decrease in CH_4 production relative to the control, typically a grass (83% of all studies); with the predominant grass being perennial ryegrass (61% of all studies). The range of change for each pasture species/grouping is in parenthesis. The plant secondary compounds (PSC) that potentially contribute to the anti-methanogenic properties of the pasture species/groupings; rainfall and soil condition the pastures are suited to; a relative rating of production and persistence (* poor to ***** Excellent); and animal health considerations are also indicated.

[1]Banik *et al.* (2013*a*); [2]Loza *et al.* (2021); [3]MacAdam *et al.* (2022); [4]Pinares-Patiño *et al.* (2003); [5]Vargas *et al.* (2018); [6]Waghorn *et al.* (2002); [7]Amaleviciute-Volunge *et al.* (2020); [8]Dal Pizzol *et al.* (2017); [9]Maxin *et al.* (2020); [10]McCaughey *et al.* (1999);[11]Medjekal *et al.* (2018); [12]Melesse *et al.* (2017); [13]Muir *et al.* (2020); [14]Niderkorn *et al.* (2011); [15]Singh *et al.* (2012); [16]Suybeng *et al.* (2021); [17]Hammond *et al.* (2011); [18]Niderkorn *et al.* (2017); [19]Pavao-Zuckerman *et al.* (1999); [20]Purcell *et al.* (2012); [21]Chung *et al.* (2013); [22]Durmic *et al.* (2016); [23]Niderkorn *et al.* (2019); [24]Prusty *et al.* (2014); [25]Sun *et al.* (2011); [26]Sun *et al.* (2012); [27]Tava *et al.* (2022); [28]Latif *et al.* (2020); [29]Abbas *et al.* (2015); [30]Scharenberg *et al.* (2007); [31]Kara *et al.* (2018).

[A]Taken from NSW Department of Primary Industries' Pasture Species and varieties (https://www.dpi.nsw.gov.au/agriculture/pastures-and-rangelands).

[B]One study (Medjekal *et al.* 2016) observed a very high relative increase (126%) in CH_4 production and resulted in average mean CH_4 emission across all studies of +6% (compared to a control). When this single study was excluded, a mean reduction in emissions of 4% was observed. The *median* reduction in emissions including the Medjekal *et al.* (2016) study was −3%.

CT, condensed tannins; Sap, saponins; T, tannins; Phen, phenolics; Al, aluminium.

failed to persist in damp soils and had limited cool season growth. Hayot Carbonero *et al.* (2011) identified it as being tolerant of cold, drought and low soil fertility. Dear *et al.* (2003) suggested that sainfoin was a potential alternative to lucerne in the well-drained, fine-textured, neutral to alkaline soils in low rainfall mallee areas of Victoria, South Australia and Western Australia. Low productivity and variable establishment were considered issues for adoption (Reed and Flinn 1993; Hayot Carbonero *et al.* 2011; Mora-Ortiz and Smith 2018). Both sainfoin and sulla (*H. coronarium*, mentioned below) can be more productive under a less intensive cutting regime, suggesting that both may lack grazing tolerance, due to their erect growth habit (Reed and Flinn 1993).

The Australian Pastures Genebank previously reported 203 accessions of sainfoin, but in 2022 only 29 accessions were active, and only three available for distribution (APG 2022). The remaining 174 accessions are historic records, with no seed stored. There is a requirement to improve the diversity of this species if its potential is to be fully explored, particularly focusing on material collected from Mediterranean environments, as this material will be most suited to the dry summers and wet winters of southern Australian agricultural regions.

Sulla

Cultivars of sulla have been released in Australia (Nichols *et al.* 2012) but few are currently commercially available. Sulla has been reported to have a high level of CT (i.e 6.8%; Waghorn *et al.* 2002), which can reduce CH_4 production by 32% compared to perennial ryegrass and white clover pasture with a similar quality (Table 1). When mixed evenly with lucerne, the CH_4 reduction remained similar, at 26%, highlighting the potential role of mixtures. Sulla also contains saponins (Tava *et al.* 2022) which may also contribute to lower CH_4.

Sulla is noted for its biennial habit, high biomass, deep taproot and bioactive ingredients (anthelmintic and non-bloating) and production systems have been developed (de Koning *et al.* 2008). Sulla growth can be slow in the first year and first year DM on offer can be increased by sowing with a cover crop that also enhances the summer survival of sulla plants (de Koning *et al.* 2008). Sulla–grass-based pastures in South Australia had higher sheep liveweight gain than grass–subterranean clover pastures and also higher wool growth and less soiling in the breech area (de Koning *et al.* 2010).

Lucerne

Lucerne is a widely utilised species in Australia (Nichols *et al.* 2012), sown over an area of 3.2 million ha with the potential for a further 27 million ha (Robertson 2006). Several *in vivo* studies of freshly grown lucerne have reported that it can decrease CH_4 emissions, compared to a range of primarily grass species, but it exhibits considerable variation in its ability to reduce enteric CH_4 (Table 1). Lucerne contains saponins and this is thought to be responsible for reductions in CH_4. This is supported by observations that ensiled lucerne has up to 7.3 mg/g DM more saponins than fresh lucerne, which reduced CH_4 production without negatively affecting the basic fermentation parameters (Kozłowska *et al.* 2020). Several studies have found lucerne hay has reduced CH_4 emission when added to a mixed ration diet (Malik and Singhal 2009, 2016; Kumar *et al.* 2018); but the lucerne diet was often higher in quality so whether the CH_4 reductions occurred because of this improved quality or a greater saponin content or a combination of both remains unclear. As lucerne is a commonly used species with a well understood agronomy, superior quality attributes leading to high levels of animal performance, available seed and potential to reduce CH_4 emissions compared to other legume pastures, it is expected to play a major role in emissions reduction from livestock systems in the future.

Perennial herbs

Perennial herbs provide high nutritive feed during late spring and summer (Cranston *et al.* 2015) and in general contain high mineral content (Pirhofer-Walzl *et al.* 2011), including trace elements such as copper (Cu) and selenium (Se) (Hoskin *et al.* 2006). Due to superior animal performance, perennial herbs are being included in pasture mixes as a specialised fodder for finishing lambs and beef cattle (Li and Kemp 2005). In addition, perennial herbs are often rich in secondary phenolic compounds, such as CT, that could potentially reduce CH_4 emissions (Minnée *et al.* 2020; Loza *et al.* 2021).

Chicory

Chicory (*Cichorium intybus*) has the potential to mitigate CH_4 emissions from ruminants as it contains tannins, saponins and other phenolic compounds (Abbas *et al.* 2015; Table 1). Waghorn *et al.* (2002) reported that chicory can reduce CH_4 emission of sheep by up to 30% (measured using the sulfur hexafluoride (SF_6) tracer technique) compared with a mixed ration of perennial ryegrass and white clover. In addition to secondary compounds, the reduction in CH_4 emission from chicory has been associated with high ratios of readily fermentable and structural carbohydrates that increased rumen particle breakdown rate and reduced retention time of particulate matter in the rumen (Barry 1998; Ramirez-Restrepo and Barry 2005). In contrast, Sun *et al.* (2011) found that there were no differences in CH_4 production between chicory and ryegrass forages (22.8 vs 23.8 g CH_4/kg DM intake) measured from sheep in an open circuit sheep respiration chamber system.

Nevertheless, chicory has demonstrated great potential to reduce CH_4 emission intensity due to its superior animal performance. For example, Jonker *et al.* (2019) reported that the milk production from chicory was greater than that from ryegrass–white clover pastures (16.7 vs 15.4 L/day, $P < 0.001$), but there were no differences in total CH_4 emissions between perennial herbs and ryegrass–white clover pastures from cows over 162 days of lactation, indicating perennial herbs can reduce CH_4 emission intensity compared to traditional ryegrass–white clover pastures.

Chicory is a deep-rooted perennial herb that is adapted to a wide range of climate and soil conditions. Chicory can produce up to 19 t DM/ha.year in favourable conditions (Li and Kemp 2005; Lee *et al.* 2015). The animal performance is superior with liveweight gain up to 290 g/day for lambs and 900 g/day for calves in spring and summer in New Zealand (Li and Kemp 2005; Cranston *et al.* 2015). Including chicory in a pasture mix can increase the voluntary intake, with improved N use efficiency due to its fast particle breakdown, hence improving animal performance (Niderkorn *et al.* 2019).

Grazing management of chicory presents a great challenge to farmers. Chicory can be grazed hard and frequently during its fast-growing period in spring and early summer but grazing in autumn and winter is detrimental to its persistence (Li and Kemp 2005). To maintain a vegetative, high feed quality forage after vernalisation, a more intensive grazing regime is recommended, though the resulting decline in water soluble carbohydrate reserves of roots is likely to compromise its longevity (Mangwe *et al.* 2020). The poor persistence that has been observed is most likely due to improper grazing management. With careful management, such as not grazing during a wet winter, chicory can last for 4–6 years with great productivity under New Zealand conditions (Ramirez-Restrepo and Barry 2005).

Another challenge for the management of chicory is to find a suitable companion species. Due to its high nitrogen (N) demand, legume species are the obvious choice. However, deep-rooted lucerne competes with chicory for water, and aerial seeded annual legumes are a mismatch with the timing of grazing and seed set. Due to its winter-dormancy (Rumball 1986), winter active grasses appear unsuitable as companion species for chicory (Li and Kemp 2005; Cranston *et al.* 2015). Annual legumes with high levels of hard seed, such as biserrula, or legumes that bury seeds underground, such as subterranean clover, are likely to be the most suitable companion species, however they will need further investigation in the field.

Plantain

Plantain (*Plantago lanceolata*) is a summer active perennial herb that can maintain high nutritive values during warm summer conditions (Cranston *et al.* 2015) and whilst it has little to no CT, it is rich in other phenolic compounds and saponins (Kara *et al.* 2018; Loza *et al.* 2021) so has potential to reduce CH_4 emissions (Table 1). Cows grazing a mix of plantain, chicory and white clover produced 15% less CH_4 daily, on average, compared with cows grazed on perennial grass-based pastures, most likely due to the content of CT and HT in addition to the improved quality of the diet (Wilson *et al.* 2020). Pasture productivity can also be high with plantain. Moorhead and Piggot (2009) reported that plantain-based pastures had higher DM production, by 1.8 t DM/ha in summer and 0.9 t DM/ha in autumn, compared to perennial ryegrass-based pastures, but there were no production differences in winter and spring averaged across six sites in Northland, New Zealand. Adding plantain to perennial ryegrass–white clover pastures has potential to increase production levels and to improve DM distribution over time (Moorhead and Piggot 2009). Pure swards of plantain have been shown to yield up to 19 t DM/ha.year in favourable conditions in New Zealand (Powell *et al.* 2007; Minneé *et al.* 2013; Lee *et al.* 2015). However, yields of 5–9.7 t/ha have been reported in dry environments such as Australia (Reed *et al.* 2008) and North America (Sanderson *et al.* 2003). Despite its high organic matter digestibility (80%) when in a vegetative state, growth of lambs was much lower than those grazing chicory but was similar to that for lambs grazing perennial ryegrass (Fraser and Rowarth 1996). Lee *et al.* (2015) also found that when sown as a pure sward, the crude protein content of plantain can be low (<15%), potentially limiting animal production (Cranston *et al.* 2015).

Similar to chicory, the poor persistence of plantain is an obstacle for adoption in grazing systems. Plantain requires regular rotational grazing to persist and maintain feed quality, however grazing during winter would reduce the persistence markedly. Labreveux *et al.* (2004) concluded that the plantain cultivars tested may not be appropriate for perennial pastures in north-eastern USA due to very low plant survival. In contrast, Moorhead and Piggot (2009) found that plantain remained the major sward component and produced 1.2 t DM/ha higher yield than perennial ryegrass–white clover pastures in Year 3 across six sites in Northland New Zealand.

Annual legumes

Biserrula

Biserrula contains a range of PSC including both phenolics and saponins (Ghamkhar *et al.* 2018; Latif *et al.* 2020) that greatly inhibit the production of CH_4 within *in vitro* studies compared to many other commonly grown forages (Banik *et al.* 2013*a*, 2013*b*, 2019; Vercoe 2016). Pen feeding experiments have also demonstrated reductions in CH_4 emissions on a DMI basis of 42%, 24% and 51% compared with bladder clover (*Trifolium spumosum*), subterranean clover and French serradella (*Ornithopus sativus*), respectively (Hutton *et al.* 2014). Methane production from biserrula was unaffected by growth stage and produced 10.5 mL/g DM on average, compared to 45.5 mL/g DM for subterranean clover *in vitro* (Banik *et al.* 2019).

Biserrula is well adapted to low fertility, acid soils and a wide range of rainfall conditions (325–700 mm) (Loi *et al.* 2010), but currently is not widely grown (Thomas *et al.* 2021).

Biserrula is capable of producing both high quantity (>5 t/ha) and high quality (digestibility of organic dry matter [DOMD] >60% along with crude protein 15–23% and metabolisable energy [ME] >11 MJ/kg DM) with neutral detergent fibre [NDF] values that are comparable or lower than lucerne during the early to mid-growing season (Vercoe 2016; Hackney *et al.* 2021; McGrath *et al.* 2021). However, these grazing studies have found that livestock production is less than might be expected based on previously reported forage parameters. Work by McGrath *et al.* (2021) observed that liveweight gains in sheep after 61 days of grazing a biserrula monoculture were ~6–9 kg lower compared to grazing lucerne monocultures and ~3 kg lower than subterranean clover monoculture. Further, Vercoe (2016) observed that average daily gain (ADG g/day) was always lower compared to other annual legumes in monoculture, e.g. subterranean clover and serradella (*Ornithopus* spp.) but higher rates of ADG were achieved when a 2:1 ratio of annual ryegrass:biserrula was fed. While the reasons for this are not well understood it likely relates to a number of factors. These include: (a) lower palatability (Vercoe 2016); (b) decreased fermentation of biserrula resulting in lower *in vitro* gas production (Banik *et al.* 2013*a*, 2013*b*) and a subsequent decrease in pasture intake (McGrath *et al.* 2021); (c) reduced grazing if stock are impacted by a photosensitisation event (Hackney *et al.* 2007; Kessell *et al.* 2015) and; (d) development of an aversion to it, in particular in sheep (Revell and Thomas 2004). Aversion to biserrula appears to be more likely to occur when it is the dominant species in the pasture. This aversion may be minimised by ensuring a more heterogenous mixture of species is present in pastures (Swinny *et al.* 2015; Thomas *et al.* 2015).

Serradella

The serradella species are prostrate annual legumes that produce small seeds in woody pods (Nutt *et al.* 2021). While serradella has not demonstrated reductions in CH_4 emissions *in vitro* (Table 1), there is potential to use genetic resources to breed lower CH_4 cultivars. Serradella species are suited to deep, acidic sandy soils (Nichols *et al.* 2007). They are widely adapted and used in ley or phase farming in Western Australia, particularly French serradella and yellow serradella (*Ornithopus compressus*). In a study of legume persistence across permanent grassland pastures of eastern NSW, Hayes *et al.* (2023) identified the serradella species as one of the most promising alternative legume species for use in mixed grazed pastures across that extensive region. The relatively lower critical phosphorus requirements of serradella compared with subterranean clover (Bolland and Paynter 1992; Sandral *et al.* 2019) led Sandral *et al.* (2019) to postulate that it may be more competitive with cocksfoot (*Dactylis glomerata*) and phalaris (*Phalaris aquatica*) in mixed pastures. Lower fertiliser costs would provide an added advantage. Further, suitability mapping of serradella by Hill (1996) identified a large area of NSW suited to serradella. The importance of vernalisation and photoperiod in flowering date stability has recently been studied for adaptability in eastern Australia, to improve the selection of cultivars for target environments (Goward *et al.* 2023). There is also evidence to suggest within-cultivar variability in flowering date and flowering date stability (Haling *et al.* 2022), which can be used to breed better cultivars.

Medics

Annual medics have been sown over an estimated area of 24.6 million ha in Australia (Nichols *et al.* 2012). They contain saponins (Tava and Pecetti 2012) and so may reduce CH_4 emissions. However, Banik *et al.* (2013*a*) found no reductions in CH_4 emissions (*in vitro*) for burr medic (*Medicago polymorpha*) compared to perennial ryegrass. Studies in annual medics show large variation in total saponin content, saponin type and biological activity of different saponins, which is likely to influence their CH_4 reduction potential. As an example, Pecetti *et al.* (2010) found the saponin content in spotted medic (*Medicago arabica*) did not vary through the growing season (24.3–28.3 mg/g DM) but decreased markedly at senescence (10.7 mg/g DM) and had higher saponin levels than those observed in lucerne or barrel medic. Tava and Pecetti (2012) also measured the saponin content of 12 annual medic species and found levels varied from 0.38–1.35% of DM. Lei *et al.* (2019) screened 201 barrel medic (*Medicago truncatula*) accessions and found that total saponins in accessions with the lowest concentration were only 60% of those accessions with the highest concentration. Maestrini *et al.* (2020) reported that crude saponin levels were 2.1%, and 1.7% of DM respectively in burr medic cultivars Angola and Santiago, and all saponins inhibited gastrointestinal nematode eggs in sheep.

Nine species of annual medics have been commercialised in Australia with barrel medic and strand medic (*Medicago littoralis*) widely grown. Burr medic is considered moderately popular, and the other species are considered special purpose or local use (Nichols *et al.* 2012). The main use of medics is as ley pastures for neutral and alkaline soils (Nichols *et al.* 2012). Burr medics are more tolerant of low pH (4.8–5.2 measured in $CaCl_2$) than barrel and strand medics (5.8 measured in $CaCl_2$) (Howie *et al.* 2007; Nichols *et al.* 2012) and have greater waterlogging tolerance than other medic species (Francis and Poole 1973). For these reasons, and that they are widely naturalised in Australia, burr medics have the potential to be more widely grown than they currently are. If studies confirm CH_4 abatement from grazing burr medics, then long season cultivars could be developed for high rainfall areas. Spotted medic has performed well on acidic waterlogged soils (Dear *et al.* 2003) and a breeding program has commenced (Nair *et al.* 2006) but no cultivars have been released.

Subterranean clover

Of the other mainstream pasture species, subterranean clover is of interest because it is the most widely sown annual legume in Australia at 29.3 million ha (Nichols *et al.* 2012), and when fed to sheep has been found to reduce CH_4 production by 30% compared with feeding ryegrass (Muir *et al.* 2020). Moreover, while the methanogenic potential of subterranean clover is variable (Table 1), it is also heritable so it can be manipulated by plant breeding (Kaur *et al.* 2017; Durmic *et al.* 2022). The other plant traits that contribute to the current success of subterranean clover include its prostate growth making it tolerant to grazing, its ability to bury burrs and protect seed from grazing, a diversity of flowering times to enable it to be grown in many different environments (250–1200 mm of rainfall) and being productive in mixtures (Nichols *et al.* 2013). There are at least 45 registered cultivars of subterranean clover covering the full environmental gradient that the species can be grown in. Little is known about the range of PSC available in genetic resources. Overall, there is great potential to develop new subterranean clover lines, but the persistence of background populations may make it difficult to determine if a new variety is present, as has been the case with older oestrogenic subterranean clover.

Integrated system assessment

Farm-scale emissions from low methane legumes

The climate change mitigation potential needs to be considered at a farm-scale when shifting from currently sown legumes to pasture species capable of reducing livestock CH_4 emissions. Farm-scale emissions will be determined not just by enteric CH_4 emissions but also other emissions sources (e.g. N_2O emissions from soils), including other factors, such as productivity, related to GHG emission intensity. The economic impacts of changing pasture types also need to be considered. Few existing studies have taken this approach to assessing the climate change mitigation potential of replacing currently recommended pasture species with species that have anti-methanogenic properties.

Doran-Browne *et al.* (2015) found that replacing a ryegrass and subterranean clover pasture with *L. corniculatus* decreased enteric CH_4 emissions by up to 19% (up to 5 t CO_2-e/ha), and reduced emissions intensity by 5–20% for prime lamb production across a range of simulated intakes of *L. corniculatus* (20, 30 and 40% of the diet). Income from productivity gains was 15–30 times higher than from potential emissions trading (at A$6/t CO_2-e). Without productivity gains, potential C offset income would not have covered the costs of establishing lotus pasture, though rising C prices may change this. The results from the study highlighted that poor pasture persistence limited profitability (Doran-Browne *et al.* 2015).

As a comparison, Vercoe (2016) studied the effect of increased proportion of biserrula in pastures up to 80%, on a typical sheep property in the 600 mm rainfall zone in Western Australia and found that while biserrula reduced CH_4 it also reduced weight gain of animals. The study found a linear reduction in CH_4 intensity with increasing biserrula from 23 kg CO_2-e/kg meat for the base system to 19.7 kg CO_2-e/kg meat with 80% biserrula or a 0.04 kg CO_2-e/kg meat reduction for every percentage of increase of biserrula. However, the lower productivity of biserrula meant that farm profit and total emissions per farm also declined with an increasing proportion of biserrula due to a lower stocking rate (Vercoe 2016). Other studies have identified the potential for biserrula to maintain animal production (Hackney *et al.* 2021) and even lengthen the grazing season as it is more deep-rooted (Hackney *et al.* 2013), but any reductions in quality will lower production (Harrison *et al.* 2015; Thomas *et al.* 2021).

Case study

A case study was undertaken to examine how productivity changes (e.g. lamb production) affect total emissions and emissions intensity by introducing biserrula to pasture as an alternative to subterranean clover and lucerne. Data were obtained from a field experiment (McGrath *et al.* 2021) in which lambs grazed biserrula, subterranean clover and lucerne pastures over a 3-month period and pasture parameters (e.g. DM production, DM digestibility and crude protein content) and animal performance (e.g. liveweight gain, LWG) were recorded. Emissions associated with animal production were calculated on a monthly basis using the equations from the Australian National Greenhouse Gas Inventory (NGGI; Australian Government 2020) and the relevant equations to calculate the emissions were parameterised using data from McGrath *et al.* (2021). A Global Warming Potential over 100 years (GWP_{100}) value of 28 for biogenic CH_4 was used (IPCC 2014). Emissions were calculated on an emissions intensity (kg CO_2-e/kg LWG) and area (kg CO_2-e/ha) basis.

Emissions from the relevant sources on a LWG basis are presented in Table 2. Assuming grazing biserrula did not reduce enteric CH_4 emissions, results indicate that emissions intensity for biserrula was 61% greater than for subterranean clover and 71% greater than for lucerne. A 45% reduction in enteric CH_4 emissions was demonstrated by Hutton *et al.* (2014) when biserrula replaced subterranean clover in a 1.2 times maintenance ration. When this 45% reduction in enteric CH_4 emissions is accounted for, this reduced the emissions intensity of biserrula to the equivalent of subterranean clover but it was still 7% greater than for lucerne.

However, if animal production is assumed to match subterranean clover in terms of growth per unit DMI, emissions intensity was reduced by 64% relative to lucerne.

Table 2. Greenhouse gas emissions intensity (kg CO_2-e/kg LWG) with breakdown by emissions source for one kg of lamb liveweight production on subterranean clover (Sub), biserrula and lucerne pastures, where (A) biserrula is not assumed to reduce enteric methane emissions, (B) biserrula is assumed to reduce enteric methane emissions by 45% per unit DMI and (C) biserrula is assumed to give 45% emissions reduction, and animal production equivalent to subterranean clover.

	Sub	Biserrula A	Lucerne	Biserrula B	Biserrula C
Enteric methane	3.5	5.6	3.2	3.1	1.9
Indirect N_2O emissions[A]	0.1	0.2	0.1	0.2	0.1
Manure methane	0.2	0.2	0.1	0.2	0.2
Residue emissions[B]	3.8E−06	7.6E−06	6.3E−06	7.6E−6	3.8E−6
Direct nitrous oxide[C]	0.4	0.7	0.5	0.7	0.4
Emissions intensity	4.2	6.7	3.9	4.2	2.6

[A]Emissions associated with the volatilisation of N in manure and subsequent emissions of N_2O.
[B]N_2O emissions from N released from residues.
[C]N_2O emissions from N deposited in manure.

Thus, grazing biserrula may have the potential to reduce GHG emissions associated with animal production if issues such as photosensitivity, preferential grazing and reduced fermentation can be ameliorated.

Methane emissions from relevant sources on an area basis are presented in Table 3. Subterranean clover and biserrula pastures had the same stocking rate however subterranean clover pastures gave a higher LWG so, despite the lower emissions intensity of LWG on a subterranean clover pasture, the total emissions for subterranean clover and biserrula pasture were similar on a per hectare basis. Further, despite lamb produced on lucerne pasture having the lowest emissions intensity, the high stocking rate meant that emissions per hectare were more than double that for subterranean clover or biserrula pastures. Assuming a 45% decrease in enteric CH_4 for biserrula resulted in a 36% and 70% reduction in total emissions relative to subterranean clover and lucerne respectively, and where LWG for biserrula was assumed to be the same for subterranean clover, total GHG emissions were reduced by 38 and 71% relative to subterranean clover and lucerne respectively.

This case study demonstrates how the potential for a reduction in the GHG emissions intensity and/or total emissions could be assessed under the proposed framework using calculations that align with the NGGI. For a complete farm-scale analysis other emissions sources such as inputs of fuel and fertilisers, and changes to soil organic carbon (SOC) would also need to be included for this temperate forage, as has been demonstrated for *Leucaena leucocephala* (Harrison *et al.* 2015). Changing to a pasture that has lower persistence would increase the frequency of re-sowing of pastures, which may result in a decline in SOC due to greater soil disturbance. Reduced persistence leading to shorter pasture phases in a mixed farming (crop/livestock) production system would also likely reduce SOC. Badgery *et al.* (2014) found that SOC decreased by 0.54 t C/ha.year to 0–30 cm for every year of cropping but increased at 0.78 t C/ha.year for pasture. Chan *et al.* (2011) found SOC sequestration rates of 0.22, 0.25, and 0.40 t C/ha.year at 0–30 cm for 33%, 50%, and 67% pasture in a cropping rotation, respectively. Changing to a species with lower persistence, where the duration of the cropping phase does not change, will also reduce the farm-scale emissions because fewer animals will be run, producing less enteric CH_4.

For animal emissions, when we assumed that biserrula reduced enteric CH_4 emissions by 45%, this did not lower the emissions intensity sufficiently so that it was comparable to lucerne. A 50% reduction in enteric CH_4 would be required

Table 3. Total GHG emissions (kg CO_2-e/ha) for lamb production grazing subterranean clover (Sub), biserrula or lucerne pasture. Data from McGrath *et al.* (2021), where (A) biserrula is not assumed to reduce enteric methane emissions. (B) Biserrula is assumed to reduce enteric methane emissions by 45% per unit DMI or (C) biserrula is assumed to give 45% emissions reduction, and animal production equivalent to subterranean clover.

	Sub	Biserrula A	Lucerne	Biserrula B	Biserrula C
Emissions intensity (kg CO_2-e/kg LWG)	4.2	6.7	3.9	4.2	2.6
Stocking rate (sheep/ha)	17.7	17.7	32.3	17.7	17.7
LWG (kg)	12.2	7.7	15.3	7.7	12.2
Total	892.3	911.4	1925.8	569.3	554.7

Data from McGrath *et al.* (2021).

for the emissions intensity of lamb produced on a biserrula pasture to match that of lamb produced on a lucerne pasture. Other *in vivo* research into effects on enteric CH_4 suggested much lower reductions of between 16% and 28% depending on the quality of intake (Vercoe 2016). This suggests that from a systems perspective, biserrula may not have the potential to reduce the emissions intensity of lamb production relative to subterranean clover and lucerne pastures unless the factors that limit livestock production on biserrula are overcome. The GHG emissions of animal production systems, other than enteric CH_4, are influenced by biophysical characteristics of plants (e.g. root:shoot ratio) and animals (e.g. N retention). For the present study, default values for these equation parameters for pastures, from the NGGI, were used, but these parameters may not be appropriate for the pasture species used in this study. Ideally, these additional parameters will be refined based on future research that estimates the emissions reductions from using low CH_4 yielding species.

Results from this case study highlight an important point in assessing the climate mitigation potential of low CH_4 pasture species – that a reduction in the GHG emissions intensity of animal production does not necessarily lead to a reduction in total emissions at the farm-scale, and can, instead, increase farm-level emissions. However, this could still be part of a larger scale climate change mitigation strategy. Simmons *et al.* (2020) demonstrated that the farm is not the most appropriate scale to estimate the climate change mitigation potential of management changes because it does not consider the global impacts of feeding and clothing the world population, projected to reach 10 billion people by 2050 (United Nations 2017). Agricultural land is constrained at a global scale so de-intensifying agricultural systems requires more land to produce the same amount of commodities which increases demand for agricultural land, resulting in land clearing (Smith *et al.* 2019). This is an issue because climate impacts of converting natural land to agricultural land can be greater than the emissions reductions achieved at the farm-scale via de-intensification (Searchinger *et al.* 2018). Although this kind of 'burden shifting' remains theoretical for agricultural production it has been demonstrated for other land-based commodities such as forestry (Meyfroidt *et al.* 2010). This means that, based on the analysis presented here, converting a production system to lucerne pastures may have the greatest climate change mitigation potential at a global scale because it uses existing agricultural land more efficiently than either subterranean clover or biserrula, thereby reducing the land required to feed and clothe the global population. Any future applications of the framework need to consider the impacts of increasing demand for agricultural land via de-intensification or sparing agricultural land via intensification.

Research gaps and future direction

This review highlights there are viable temperate legumes and herbs, that have anti-methanogenic properties, are productive, and capable of mitigating enteric CH_4 in grazing systems of temperate Australia. There are many areas for future research and development required before broadscale adoption of these species and accounting for GHG emission reductions can occur. Some of the key areas are highlighted below.

Understanding variation in CH_4 reduction under grazing

Plant secondary compounds are known to reduce CH_4 emissions through various pathways, however the form of the relationships between various PSC intake and CH_4 emission reduction remain unclear. *In vitro* experiments indicate that the higher the amount of PSC in a plant the greater the CH_4 emission reduction, but whether there is a threshold at which additional PSC no longer decrease CH_4 emissions or affect digestibility, and therefore DMI, needs to be further explored. Whether *in vitro* experiments are true indicators of *in vivo* CH_4 emission measurements can also be confusing; proper validation of any *in vitro* method must involve rigorous *in vivo* validation to enable reliable estimation of CH_4 in laboratories. There are also other factors that interact with the actions of PSC to determine *in vivo* CH_4 reduction, such as plant quality and preferential grazing. Factors such as these would have been responsible for the variability amongst *in vivo* CH_4 reductions reported by Vercoe (2016) for animals grazing biserrula over various seasons. Understanding how these factors affect CH_4 reductions is essential in being able to predict the potential CH_4 reductions associated with the introduction of a species into a system. Also, any potential animal and human health implications of PSC need to be fully understood (Durmic *et al.* 2022).

Same species or new systems?

There is an imperative for rapid action to reduce GHG emissions from agriculture as soon as possible to limit the impacts of climate change. There is a strong case for promoting the adoption of current technologies/pasture species (e.g. biserrula and chicory) that are readily available because they do not require producers to implement new seeding methods and/or invest in new equipment. However, methods need to be developed to accurately account for CH_4 emissions reductions and ensure that adverse GHG or production impacts do not occur. Furthermore, adapting parameters for the NGGI and other accounting frameworks may need to be modified for low CH_4 yielding species.

The role of pasture mixtures

Throughout the temperate grazing systems of Australia, pastures are predominantly mixtures of species, generally containing an annual or perennial legume combined with one or more grass species. There is also increasing interest in including herbs in these pasture mixtures. Many studies have shown that livestock often prefer a 'choice' of pasture species when grazing in order to satisfy a range of forage requirements (quality, quantity, roughage, etc.) (Edwards *et al.* 2008; Soder *et al.* 2009) and that livestock grazing mixes of species are commonly observed to have decreased rates of CH_4 emissions (Wilson *et al.* 2020). In addition, species mixes maximise the productivity of a pasture system by extending out the growing period. Further work is needed to build regionally suitable, diverse pasture mixtures and management that can sustain higher proportions of legumes and herbs.

Breeding to improve CH_4 reduction

This paper highlights reasonable potential for some species/cultivars to reduce CH_4, but there is also great opportunity to develop breeding programs that will encourage the production of new cultivars with increased levels of anti-methanogenic activity. As an example, Roldan *et al.* (2022) increased the CT level in white clover leaf to >2% of DM in two generations of breeding, which in turn reduced *in vitro* CH_4 production by 19%. The same breeding potential has been identified for subterranean clover (Kaur *et al.* 2017) and likely exists for lucerne and other widely grown legume species. New breeding programs are required to develop cultivars that have increased anti-methanogenic properties. Even with speed breeding (Pazos-Navarro *et al.* 2017; Ghosh *et al.* 2018; Watson *et al.* 2018) it will be many years before new cultivars come onto the market. As such new cultivars are not likely to be major drivers in the mid-term (5–10 years) and are really part of longer-term solutions (>10 years) to deal with emission reductions.

Systems analyses

Determining total *in vivo* GHG reductions for low CH_4 yielding species in a variety of environments is yet to be assessed. The case study in this paper clearly highlights the importance of maintaining high productivity to reduce CH_4 emission intensity, but also found that high productivity increased whole-farm GHG emissions. Meeting the emission reduction targets of government and the supply chain for ruminant products will require a reduction in total GHG emissions but maintaining productivity is important to ensure the most efficient use of existing agricultural land and avoid the need for more land to be brought into agricultural production to meet the demands of a growing global population. The trade-off between total GHG emissions and emission intensity, including the effects on soil C stocks, need to be investigated further and new integrated metrics developed and tested in different environments.

Standardised measurements

Standardised and validated protocols are required for the estimation of CH_4 reduction potential. The extent of CH_4 reduction is always assessed relative to some other forage and the use of a standardised comparison pasture species that has low PSC contents, is necessary to quantify differences within and between studies. While perennial ryegrass is often used as a comparative species in temperate pasture regions, it is not grown in lower rainfall grazing systems of temperate Australia. A commonly grown forage within a region would be a more appropriate comparison.

References

Abbas ZK, Saggu S, Sakeran MI, Zidan N, Rehman H, Ansari AA (2015) Phytochemical, antioxidant and mineral composition of hydroalcoholic extract of chicory (*Cichorium intybus* L.) leaves. *Saudi Journal of Biological Sciences* **22**, 322–326. doi:10.1016/j.sjbs.2014.11.015

Aboagye IA, Beauchemin KA (2019) Potential of molecular weight and structure of tannins to reduce methane emissions from ruminants: a review. *Animals* **9**, 856. doi:10.3390/ani9110856

Almeida AK, Hegarty RS, Cowie A (2021) Meta-analysis quantifying the potential of dietary additives and rumen modifiers for methane mitigation in ruminant production systems. *Animal Nutrition* **7**, 1219–1230. doi:10.1016/j.aninu.2021.09.005

Amaleviciute-Volunge K, Slepetiene A, Butkute B (2020) Methane yield of perennial grasses with as affected by the chemical composition of their biomass. *Zemdirbyste-Agriculture* **107**, 243–248. doi:10.13080/z-a.2020.107.031

Armstrong CS (1974) 'Grasslands Maku' tetraploid lotus (*Lotus pedunculatus* Cav.). *New Zealand Journal of Experimental Agriculture* **2**, 333–336. doi:10.1080/03015521.1974.10427691

Australian Government (2020) Australian national greenhouse accounts national inventory report 2018. Department of the Environment and Energy.

Australian Pastures Genebank (2022) Sainfoin. Available at https://www.pir.sa.gov.au/research/australian_pastures_genebank [Accessed 30 August 2022]

Australian Seeds Authority Ltd. (2021*a*) Areas registered in Australia for certification under OECD, AOSCA and Australian seed certififcation schemes – 2017/19 to 2021/22. Available at https://aseeds.com.au/wp-content/uploads/asgarosforum/82/AREA-REGISTERED-FOR-CERTIFICATION-TO-15-DEC-2021-Amended-Report-22Dec2021.pdf [Accessed 30 August 2022]

Australian Seeds Authority Ltd. (2021*b*) Certified seed produced in Australia under OECD, AOSCA and Australian seed certification schemes in the 12 months to 30 September 2021. Available at https://aseeds.com.au/wp-content/uploads/asgarosforum/82/TOTAL-CERTIFIED-SEED-AUSTRALIA-2017-18-to-2020-21-20Dec2021.pdf [Accessed 30 August 2022]

Australian Seeds Authority Ltd. (2021*c*) National list of plant varieties eligible for seed certification in Australia. Available at https://aseeds.com.au/wp-content/uploads/asgarosforum/23/ASA-NATIONAL-LIST-OF-VARIETIES-10Sept2021.pdf [Accessed 30 August 2022]

Ayres JF, Blumenthal MJ, O'Connor JW, Lane LA, Nicol HI (2006*a*) Birdsfoot trefoil (*Lotus corniculatus*) and greater lotus (*Lotus uliginosus*) in perennial pastures in eastern Australia. 1. Effects of grazing management on persistence. *Australian Journal of Experimental Agriculture* **46**, 503–519. doi:10.1071/EA04241

Ayres JF, Blumenthal MJ, Lane LA, O'Connor JW (2006*b*) Birdsfoot trefoil (*Lotus corniculatus*) and greater lotus (*Lotus uliginosus*) in perennial pastures in eastern Australia. 2. Adaptation and applications of lotus-based pasture. *Australian Journal of Experimental Agriculture* **46**, 521–534. doi:10.1071/EA04242

Badgery WB, Simmons AT, Murphy BW, Rawson A, Andersson KO, Lonergan VE (2014) The influence of land use and management on soil carbon levels for crop-pasture systems in Central New South

Wales, Australia. *Agriculture, Ecosystems & Environment* **196**, 147–157. doi:10.1016/j.agee.2014.06.026

Badgery W, Michalk D, Kemp D (2015) Sustainable management of temperate grasslands in Australia. In 'Grassland: a global resource perspective'. (Eds PK Gosh, SK Mahanta, JB Singh, PS Pathak) pp. 141–192. (Range Management Society of India: Jhansi, India)

Banik BK, Durmic Z, Erskine W, Ghamkhar K, Revell C (2013*a*) *In vitro* ruminal fermentation characteristics and methane production differ in selected key pasture species in Australia. *Crop & Pasture Science* **64**, 935–942. doi:10.1071/CP13149

Banik BK, Durmic Z, Erskine W, Nichols P, Ghamkhar K, Vercoe P (2013*b*) Variability of *in vitro* ruminal fermentation and methanogenic potential in the pasture legume biserrula (*Biserrula pelecinus* L.). *Crop & Pasture Science* **64**, 409–416. doi:10.1071/CP13073

Banik BK, Durmic Z, Erskine W, Revell CK, Vadhanabhuti J, McSweeney CS, Padmanabha J, Flematti GR, Algreiby AA, Vercoe PE (2016) Bioactive fractions from the pasture legume *Biserrula pelecinus* L. have an anti-methanogenic effect against key rumen methanogens. *Anaerobe* **39**, 173–182. doi:10.1016/j.anaerobe.2016.04.004

Banik BK, Durmic Z, Erskine W, Revell C (2019) Anti-methanogenic advantage of biserrula (*Biserrula pelecinus*) over subterranean clover (*Trifolium subterraneum*) from *in vitro* fermentation is maintained across growth stages and cutting treatments. *Crop & Pasture Science* **70**, 263–272. doi:10.1071/CP18069

Barry TN (1998) The feeding value of chicory (*Cichorium intybus*) for ruminant livestock. *The Journal of Agricultural Science* **131**, 251–257. doi:10.1017/S002185969800584X

Beauchemin KA, Kreuzer M, O'Mara F, McAllister TA (2008) Nutritional management for enteric methane abatement: a review. *Australian Journal of Experimental Agriculture* **48**, 21–27. doi:10.1071/EA07199

Beauchemin KA, Ungerfeld EM, Eckard RJ, Wang M (2020) Review: Fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation. *Animal* **14**, s2–s16. doi:10.1017/S1751731119003100

Black JL, Davison TM, Box I (2021) Methane emissions from ruminants in Australia: mitigation potential and applicability of mitigation strategies. *Animals* **11**, 951. doi:10.3390/ani11040951

Blumenthal MJ, McGraw RL (1999) Lotus adaptation, use and management. In 'Trefoil: the science and technology of Lotus'. (Ed. PR Beuselinck) pp. 97–119. (American Society of Agronomy Inc., Crop Science Society of America Inc.: Madison, WI, USA)

Blumenthal MJ, Bowman AM, Cole A, Jones RM, Kelman WM, Launders TE, Nicol HI (1999) Establishment, growth and persistence of greater lotus (*Lotus uliginosus*) at six sites in eastern Australia. *Australian Journal of Experimental Agriculture* **39**, 819–827. doi:10.1071/EA99013

Bolland MDA, Paynter BH (1992) Comparative responses of annual pasture legume species to superphosphate applications in medium and high rainfall areas of Western Australia. *Fertilizer Research* **31**, 21–33. doi:10.1007/BF01064224

Chan KY, Conyers MK, Li GD, Helyar KR, Poile G, Oates A, Barchia IM (2011) Soil carbon dynamics under different cropping and pasture management in temperate Australia: results of three long-term experiments. *Soil Research* **49**, 320–328. doi:10.1071/SR10185

Chapman HM, Lowthe WL, Trainor KD (1990) Some factors limiting the success of *Lotus corniculatus* in hill and high country. *Proceedings of the New Zealand Grassland Association* **51**, 147–150. doi:10.33584/jnzg.1990.51.1890

Charmley E, Williams SRO, Moate PJ, Hegarty RS, Herd RM, Oddy VH, Reyenga P, Staunton KM, Anderson A, Hannah MC (2016) A universal equation to predict methane production of forage-fed cattle in Australia. *Animal Production Science* **56**, 169–180. doi:10.1071/AN15365

Chung Y-H, Mc Geough EJ, Acharya S, McAllister TA, McGinn SM, Harstad OM, Beauchemin KA (2013) Enteric methane emission, diet digestibility, and nitrogen excretion from beef heifers fed sainfoin or alfalfa. *Journal of Animal Science* **91**, 4861–4874. doi:10.2527/jas.2013-6498

Commonwealth of Australia (2022) Quarterly update of Australia's national greenhouse gas inventory: September 2021. Available at https://www.industry.gov.au/data-and-publications/national-greenhouse-gas-inventory-quarterly-update-september-2021 [Accessed 30 August 2022]

Cranston LM, Kenyon PR, Morris ST, Kemp PD (2015) A review of the use of chicory, plantain, red clover and white clover in a sward mix for increased sheep and beef production. *Journal of New Zealand Grasslands* **77**, 89–94. doi:10.33584/jnzg.2015.77.475

Dal Pizzol JG, Ribeiro-Filho HMN, Quereuil A, Le Morvan A, Niderkorn V (2017) Complementarities between grasses and forage legumes from temperate and subtropical areas on *in vitro* rumen fermentation characteristics. *Animal Feed Science and Technology* **228**, 178–185. doi:10.1016/j.anifeedsci.2017.04.020

DAWE (2016) Landuse at a glance. Available at www.awe.gov.au/sites/default/files/abares/aclump/documents/Land%20use%20in%20Australia%20at%20a%20glance%202016.pdf [Accessed 30 August 2022]

Dear BS, Moore GA, Hughes SJ (2003) Adaptation and potential contribution of temperate perennial legumes to the southern Australian wheatbelt: a review. *Australian Journal of Experimental Agriculture* **43**, 1–18. doi:10.1071/EA01202

de Koning C, Crocker G, Schutz P, Edwards N (2008) Developing production systems for the newly released varieties of the biennial forage legume sulla (*Hedysarum coronarium* L.). In 'Proceedings of 14th Australian agronomy conference'. Adelaide, South Australia. (Ed. M Unkovich) (Australian Society of Agronomy) Available at www.regional.org.au/au/asa/2008/concurrent/pasture-production/5787dekoningct.htm [Accessed 30 August 2022]

de Koning C, Schutz P, Humphries A (2010) Performance of sheep grazing sulla (*Hedysarum coronarium*) based pastures in southern Australia. In 'Proceedings of 15th Agronomy Conference'. Lincoln, New Zealand. (Eds H Dove, RA Culvenor) (Australian Society of Agronomy) Available at www.agronomyaustraliaproceedings.org/images/sampledata/2010/farming-systems/animal-feed-quality/6990_dekoningct.pdf [Accessed 30 August 2022]

DISER (2021) National inventory report 2019. (Department of Industry, Science, Energy and Resources. Australian Government) Available at https://www.industry.gov.au/sites/default/files/April%202021/document/national-inventory-report-2019-volume-1.pdf [Accessed 30 August 2022]

Doran-Browne N, Behrendt R, Kingwell R, Eckard R (2015) Modelling the potential of birdsfoot trefoil (*Lotus corniculatus*) to reduce methane emissions and increase production on wool and prime lamb farm enterprises. *Animal Production Science* **55**, 1097–1105. doi:10.1071/AN13543

Durazzo A, Lucarini M, Souto EB, Cicala C, Caiazzo E, Izzo AA, Novellino E, Santini A (2019) Polyphenols: a concise overview on the chemistry, occurrence, and human health. *Phytotherapy Research* **33**, 2221–2243. doi:10.1002/ptr.6419

Durmic Z, Moate PJ, Jacobs JL, Vadhanabhuti J, Vercoe PE (2016) *In vitro* fermentability and methane production of some alternative forages in Australia. *Animal Production Science* **56**, 641–645. doi:10.1071/AN15486

Durmic Z, Black JL, Martin GB, Vercoe PE (2022) Harnessing plant bioactivity for enteric methane mitigation in Australia. *Animal Production Science* **62**, 1160–1172. doi:10.1071/AN21004

Eckard RJ, Grainger C, de Klein CAM (2010) Options for the abatement of methane and nitrous oxide from ruminant production: a review. *Livestock Science* **130**, 47–56. doi:10.1016/j.livsci.2010.02.010

Edwards GR, Parsons AJ, Bryant RH (2008) Manipulating dietary preference to improve animal performance. *Australian Journal of Experimental Agriculture* **48**, 773–779. doi:10.1071/EA08006

Francis CM, Poole ML (1973) Effect of waterlogging on the growth of annual *Medicago* species. *Australian Journal of Experimental Agriculture* **13**, 711–713. doi:10.1071/EA9730711

Fraser TJ, Rowarth JS (1996) Legumes, herbs or grass for lamb performance? *Proceedings of the New Zealand Grassland Association* **58**, 49–52. doi:10.33584/jnzg.1996.58.2213

Ghamkhar K, Rochfort S, Banik BK, Revell C (2018) Candidate metabolites for methane mitigation in the forage legume biserrula. *Agronomy for Sustainable Development* **38**, 30. doi:10.1007/s13593-018-0510-x

Ghosh S, Watson A, Gonzalez-Navarro OE, Ramirez-Gonzalez RH, Yanes L, Mendoza-Suárez M, Simmonds J, Wells R, Rayner T, Green P, Hafeez A, Hayta S, Melton RE, Steed A, Sarkar A, Carter J, Perkins L, Lord J, Tester M, Osbourn A, Moscou MJ, Nicholson P, Harwood W, Martin C, Domoney C, Uauy C, Hazard B, Wulff BBH, Hickey LT (2018) Speed breeding in growth chambers and glasshouses for crop breeding and model plant research. *Nature Protocols* **13**, 2944–2963. doi:10.1038/s41596-018-0072-z

Goławska S, Łukasik I, Wójcicka A, Sytykiewicz H (2012) Relationship between saponin content in alfalfa and aphid development. *Acta Biologica Cracoviensia Series Botanica* **54**, 39–46. doi:10.2478/v10182-012-0022-y

Goward LE, Haling RE, Smith RW, Penrose B, Simpson RJ (2023) Flowering responses of serradella (*Ornithopus* spp.) and subterranean clover (*Trifolium subterraneum* L.) to vernalisation and photoperiod and their role in maturity type determination and flowering date stability. *Crop & Pasture Science*, In Press.

Grainger C, Clarke T, Auldist MJ, Beauchemin KA, McGinn SM, Waghorn GC, Eckard RJ (2009) Potential use of *Acacia mearnsii* condensed tannins to reduce methane emissions and nitrogen excretion from grazing dairy cows. *Canadian Journal of Animal Science* **89**, 241–251. doi:10.4141/CJAS08110

Hackney B, Dear B, Crocker G (2007) Biserrula. Available at https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0010/178066/Biserrula.pdf [Accessed 30 August 2022]

Hackney B, Rodham C, Piltz J (2013) 'Using biserrula to increase crop and livestock production.' (Meat & Livestock Australia). Available at https://www.mla.com.au/contentassets/c5bfa697aa58405bb997d65a314f10b1/using-biserrula-to-increase-crop-and-livestock-production-1.pdf [Accessed 31 August 2022]

Hackney B, Rodham C, Dyce G, Piltz J (2021) Pasture legumes differ in herbage production and quality throughout spring, impacting their potential role in fodder conservation and animal production. *Grass and Forage Science* **76**, 116–133. doi:10.1111/gfs.12525

Haling RE, Goward L, Stefanski A, Simpson RJ (2022) Variation in flowering time and flowering date stability within a cultivar of French serradella. *Crop & Pasture Science*. doi:10.1071/CP22222

Hammond KJ, Hoskin SO, Burke JL, Waghorn GC, Koolaard JP, Muetzel S (2011) Effects of feeding fresh white clover (*Trifolium repens*) or perennial ryegrass (*Lolium perenne*) on enteric methane emissions from sheep. *Animal Feed Science and Technology* **166-167**, 398–404. doi:10.1016/j.anifeedsci.2011.04.028

Harris CA, Blumenthal MJ, Scott JM (1993) Survey of use and management of *Lotus pedunculatus* cv. Grasslands Maku in eastern Australia. *Australian Journal of Experimental Agriculture* **33**, 41–47. doi:10.1071/EA9930041

Harrison MT, McSweeney C, Tomkins NW, Eckard RJ (2015) Improving greenhouse gas emissions intensities of subtropical and tropical beef farming systems using *Leucaena leucocephala*. *Agricultural Systems* **136**, 138–146. doi:10.1016/j.agsy.2015.03.003

Hatew B, Hayot Carbonero C, Stringano E, Sales LF, Smith LMJ, Mueller-Harvey I, Hendriks WH, Pellikaan WF (2015) Diversity of condensed tannin structures affects rumen *in vitro* methane production in sainfoin (*Onobrychis viciifolia*) accessions. *Grass and Forage Science* **70**, 474–490. doi:10.1111/gfs.12125

Hayes RC, Newell MT, Haling RE, Harris CA, Culvenor RA, Li GD, Badgery WB, Munday N, Price A, Stutz RE, Simpson RJ (2023) Pasture legume persistence in Tableland environments of south-eastern Australia. *Crop & Pasture Science*, In Press.

Hayot Carbonero C, Mueller-Harvey I, Brown TA, Smith L (2011) Sainfoin (*Onobrychis viciifolia*): a beneficial forage legume. *Plant Genetic Resources* **9**, 70–85. doi:10.1017/S1479262110000328

Hill MJ (1996) Potential adaptation zones for temperate pasture species as constrained by climate: a knowledge-based logical modelling approach. *Australian Journal of Agricultural Research* **47**, 1095–1117. doi:10.1071/AR9961095

Hoskin SO, Wilson PR, Ondris M, Bunod AH (2006) The feeding value of forage herbs: studies with red deer. *Proceedings of the New Zealand Grassland Association* **68**, 199–204. doi:10.33584/jnzg.2006.68.2650

Howie J, Lloyd D, Revell C (2007) Spineless burr medic. Available at https://keys.lucidcentral.org/keys/v3/pastures/Html/Spineless_burr_medic.htm. [Accessed 30 August 2022]

Hutton PG, Lund K, Toovey A, Phillips N, Allington T, Paganoni B, Vercoe PE, Thompson A (2014) Biserrula reduces methane production from sheep when compared to other commercial legume pastures, animal production in Australia. In 'Proceedings of the 30th biennial conference of the Australian Society of Animal Production'. 8–12 September 2014, National Convention Centre, Canberra, ACT. (Eds S Hatcher, GL Krebs, BWB Holman) pp. 263–264. (The Australian Society of Animal Production: Canberra, ACT)

Ionkova I, Shkondrov A, Krasteva I, Ionkov T (2014) Recent progress in phytochemistry, pharmacology and biotechnology of *Astragalus* saponins. *Phytochemistry Reviews* **13**, 343–374. doi:10.1007/s11101-014-9347-3

IPCC (2014) Climate Change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. Available at https://epic.awi.de/id/eprint/37530/ [Accessed 30 August 2022]

Jayanegara A, Goel G, Makkar HPS, Becker K (2010) Reduction in methane emissions from ruminants by plant secondary metabolites: effects of polyphenols and saponins. No. 978-92-5-106697-3. Food and Agriculture Organization of the United Nations (FAO). Available at http://inis.iaea.org/search/search.aspx?orig_q=RN:43002797

Jayanegara A, Wina E, Takahashi J (2014) Meta-analysis on methane mitigating properties of saponin-rich sources in the rumen: influence of addition levels and plant sources. *Asian-Australasian Journal of Animal Sciences* **27**, 1426–1435. doi:10.5713/ajas.2014.14086

Jayanegara A, Goel G, Makkar HPS, Becker K (2015) Divergence between purified hydrolysable and condensed tannin effects on methane emission, rumen fermentation and microbial population *in vitro*. *Animal Feed Science and Technology* **209**, 60–68. doi:10.1016/j.anifeedsci.2015.08.002

Jonker A, Farrell L, Scobie D, Dynes R, Edwards G, Hague H, McAuliffe R, Taylor A, Knight T, Waghorn G (2019) Methane and carbon dioxide emissions from lactating dairy cows grazing mature ryegrass/white clover or a diverse pasture comprising ryegrass, legumes and herbs. *Animal Production Science* **59**, 1063–1069. doi:10.1071/AN18019

Kara K, Ozkaya S, Baytok E, Guclu BK, Aktug E, Erbas S (2018) Effect of phenological stage on nutrient composition, *in vitro* fermentation and gas production kinetics of *Plantago lanceolata* herbage. *Veterinární Medicína* **63**, 251–260. doi:10.17221/2/2017-VETMED

Kaur P, Appels R, Bayer PE, Keeble-Gagnere G, Wang J, Hirakawa H, Shirasawa K, Vercoe P, Stefanova K, Durmic Z, Nichols P, Revell C, Isobe SN, Edwards D, Erskine W (2017) Climate clever clovers: new paradigm to reduce the environmental footprint of ruminants by breeding low methanogenic forages utilizing haplotype variation. *Frontiers in Plant Science* **8**, 1463. doi:10.3389/fpls.2017.01463

Kessell AE, Ladmore GE, Quinn JC (2015) An outbreak of primary photosensitisation in lambs secondary to consumption of *Biserrula pelecinus* (biserrula). *Australian Veterinary Journal* **93**, 174–178. doi:10.1111/avj.12318

Kozłowska M, Cieślak A, Jóźwik A, El-Sherbiny M, Stochmal A, Oleszek W, Kowalczyk M, Filipiak W, Szumacher-Strabel M (2020) The effect of total and individual alfalfa saponins on rumen methane production. *Journal of the Science of Food and Agriculture* **100**, 1922–1930. doi:10.1002/jsfa.10204

Kozłowska M, Cieślak A, Jóźwik A, El-Sherbiny M, Gogulski M, Lechniak D, Gao M, Yanza YR, Vazirigohar M, Szumacher-Strabel M (2021) Effects of partially replacing grass silage by lucerne silage cultivars in a high-forage diet on ruminal fermentation, methane production, and fatty acid composition in the rumen and milk of dairy cows. *Animal Feed Science and Technology* **277**, 114959. doi:10.1016/j.anifeedsci.2021.114959

Kumar R, Singh M (1984) Tannins: their adverse role in ruminant nutrition. *Journal of Agricultural and Food Chemistry* **32**, 447–453. doi:10.1021/jf00123a006

Kumar A, Chaturvedi VB, Singh AK, Anamika, Kerketta S (2018) Effect of different levels of lucerne (*Medicago sativa*) in diet on rumen fermentation and energy metabolism of ewes. *Indian Journal of Small Ruminants* **24**, 51–56. doi:10.5958/0973-9718.2018.00034.X

Ku-Vera JC, Jimenez-Ocampo R, Valencia-Salazar SS, Montoya-Flores MD, Molina-Botero IC, Arango J, Gomez-Bravo CA, Aguilar-Perez CF, Solorio-Sanchez FJ (2020) Role of secondary plant metabolites on enteric methane mitigation in ruminants. *Frontiers in Veterinary Science* **7**, 584. doi:10.3389/fvets.2020.00584

Labreveux M, Hall MH, Sanderson MA (2004) Productivity of chicory and plantain cultivars under grazing. *Agronomy Journal* **96**, 710–716. doi:10.2134/agronj2004.0710

Latif S, Weston PA, Barrow RA, Gurusinghe S, Piltz JW, Weston LA (2020) Metabolic profiling provides unique insights to accumulation and

biosynthesis of key secondary metabolites in annual pasture legumes of Mediterranean origin. *Metabolites* **10**, 267. doi:10.3390/metabo10070267
Lee JM, Hemmingson NR, Minnee EMK, Clark CEF (2015) Management strategies for chicory (*Cichorium intybus*) and plantain (*Plantago lanceolata*): impact on dry matter yield, nutritive characteristics and plant density. *Crop & Pasture Science* **66**, 168–183. doi:10.1071/CP14181
Lees GL, Howarth RE, Goplen BP, Fesser AC (1981) Mechanical disruption of leaf tissues and cells in some bloat-causing and bloat-safe forage legumes. *Crop Science* **21**, 444–448. doi:10.2135/cropsci1981.0011183X002100030023x
Lei Z, Watson BS, Huhman D, Yang DS, Sumner LW (2019) Large-scale profiling of saponins in different ecotypes of *Medicago truncatula*. *Frontiers in Plant Science* **10**, 850. doi:10.3389/fpls.2019.00850
Li G, Kemp PD (2005) Forage chicory (*Cichorium intybus* L.): a review of its agronomy and animal production. *Advances in Agronomy* **88**, 187–222.
Li X, Norman HC, Kinley RD, Laurence M, Wilmot M, Bender H, de Nys R, Tomkins N (2018) *Asparagopsis taxiformis* decreases enteric methane production from sheep. *Animal Production Science* **58**, 681–688. doi:10.1071/AN15883
Loi A, Hogg N, Revell C, Fedorenko D (2010) Growing biserrula to improve grain and livestock production. Available at https://library.dpird.wa.gov.au/bulletins/209/ [Accessed 30 August 2022]
Loza C, Verma S, Wolffram S, Susenbeth A, Blank R, Taube F, Loges R, Hasler M, Kluß C, Malisch CS (2021) Assessing the potential of diverse forage mixtures to reduce enteric methane emissions *in vitro*. *Animals* **11**, 1126. doi:10.3390/ani11041126
MacAdam JW, Pitcher LR, Bolletta AI, Guevara Ballesteros RD, Beauchemin KA, Dai X, Villalba JJ (2022) Increased nitrogen retention and reduced methane emissions of beef cattle grazing legume vs. Grass irrigated pastures in the Mountain West USA. *Agronomy* **12**, 304. doi:10.3390/agronomy12020304
Maestrini M, Tava A, Mancini S, Tedesco D, Perrucci S (2020) *In vitro* anthelmintic activity of saponins from *Medicago* spp. Against sheep gastrointestinal nematodes. *Molecules* **25**, 242. doi:10.3390/molecules25020242
Majak W, Howarth RE, Fesser AC, Goplen BP, Pedersen MW (1980) Relationships between ruminant bloat and the composition of alfalfa herbage. II. Saponins. *Canadian Journal of Animal Science* **60**, 699–708. doi:10.4141/cjas80-081
Makkar HPS (2003) 'Quantification of tannins in tree and shrub foliage – a laboratory manual.' (Springer Science+Business Media)
Malik PK, Singhal KK (2009) Effect of lucerne (*Medicago sativa*) fodder supplementation on nutrient utilization and enteric methane emission in male buffalo calves fed on wheat straw based total mixed ration. *Indian Journal of Animal Sciences* **79**, 416–421.
Malik PK, Singhal KK (2016) Effect of alfalfa fodder supplementation on enteric methane emission measured by sulfur hexafluoride technique in murrah buffaloes. *Buffalo Bulletin* **35**, 125–134.
Mangwe MC, Bryant RH, Moreno Garcia CA, Maxwell TMR, Gregorini P (2020) Functional traits, morphology, and herbage production of vernalised and non-vernalised chicory cv. Choice (*Cichorium intybus* L.) in response to defoliation frequency and height. *Plants* **9**, 611. doi:10.3390/plants9050611
Maxin G, Graulet B, Le Morvan A, Picard F, Portelli J, Andueza D (2020) Cover crops as alternative forages for ruminants: nutritive characteristics, *in vitro* digestibility, methane and ammonia production. *Animal Production Science* **60**, 823–832. doi:10.1071/AN19091
McCaughey WP, Wittenberg K, Corrigan D (1999) Impact of pasture type on methane production by lactating beef cows. *Canadian Journal of Animal Science* **79**, 221–226. doi:10.4141/A98-107
McGrath SR, Sandral GA, Sundermann L, Quinn JC, Weston LA, Friend MA (2021) Liveweight and carcass characteristics of White Dorper and Crossbred lambs grazing lucerne, subterranean clover, biserrula or a choice of subterranean clover plus biserrula in southern Australia. *Animal Production Science* **61**, 1151–1159. doi:10.1071/AN18769
McSweeney CS, Kennedy PM, John A (1988) Effect of ingestion of hydrolysable tannins in *Terminalia oblongata* on digestion in sheep fed *Stylosanthes hamata*. *Australian Journal of Agricultural Research* **39**, 235–244. doi:10.1071/AR9880235
Medjekal S, Ghadbane M, Bodas R, Bousseboua H, López S (2018) Volatile fatty acids and methane production from browse species of Algerian arid and semi-arid areas. *Journal of Applied Animal Research* **46**, 44–49. doi:10.1080/09712119.2016.1257432
Melesse A, Steingass H, Schollenberger M, Rodehutscord M (2017) Screening of common tropical grass and legume forages in Ethiopia for their nutrient composition and methane production profile *in vitro*. *Tropical Grasslands-Forrajes Tropicales* **5**, 163–175. doi:10.17138/TGFT(5)163-175
Meyfroidt P, Rudel TK, Lambin EF (2010) Forest transitions, trade, and the global displacement of land use. *Proceedings of the National Academy of Sciences* **107**, 20917–20922. doi:10.1073/pnas.1014773107
Min BR, Pinchak WE, Fulford JD, Puchala R (2005) Wheat pasture bloat dynamics, *in vitro* ruminal gas production, and potential bloat mitigation with condensed tannins. *Journal of Animal Science* **83**, 1322–1331. doi:10.2527/2005.8361322x
Min BR, Solaiman S, Waldrip HM, Parker D, Todd RW, Brauer D (2020) Dietary mitigation of enteric methane emissions from ruminants: a review of plant tannin mitigation options. *Animal Nutrition* **6**, 231–246. doi:10.1016/j.aninu.2020.05.002
Minneé EMK, Clark CEF, Clark DA (2013) Herbage production from five grazable forages. *Proceedings of the New Zealand Grassland Association* **75**, 245–249. doi:10.33584/jnzg.2013.75.2906
Minnée EMK, Leach CMT, Dalley DE (2020) Substituting a pasture-based diet with plantain (*Plantago lanceolata*) reduces nitrogen excreted in urine from dairy cows in late lactation. *Livestock Science* **239**, 104093. doi:10.1016/j.livsci.2020.104093
MLA (2022) Livestock distribution maps. Available at https://www.mla.com.au/prices-markets/Trends-analysis/livestock-distribution-maps/ [Accessed 30 August 2022]
Moate PJ, Deighton MH, Williams SRO, Pryce JE, Hayes BJ, Jacobs JL, Eckard RJ, Hannah MC, Wales WJ (2016) Reducing the carbon footprint of Australian milk production by mitigation of enteric methane emissions. *Animal Production Science* **56**, 1017–1034. doi:10.1071/AN15222
Moorhead AJE, Piggot GJ (2009) The performance of pasture mixes containing 'Ceres Tonic' plantain (*Plantago lanceolata*) in Northland. *Proceedings of the New Zealand Grassland Association* **71**, 195–199. doi:10.33584/jnzg.2009.71.2757
Mora J, Pott DM, Osorio S, Vallarino JG (2022) Regulation of plant tannin synthesis in crop species. *Frontiers in Genetics* **13**, 870976. doi:10.3389/fgene.2022.870976
Mora-Ortiz M, Smith LMJ (2018) *Onobrychis viciifolia*; a comprehensive literature review of its history, etymology, taxonomy, genetics, agronomy and botany. *Plant Genetic Resources: Characterization and Utilization* **16**, 403–418. doi:10.1017/S1479262118000230
Moses T, Papadopoulou KK, Osbourn A (2014) Metabolic and functional diversity of saponins, biosynthetic intermediates and semi-synthetic derivatives. *Critical Reviews in Biochemistry and Molecular Biology* **49**, 439–462. doi:10.3109/10409238.2014.953628
Mueller-Harvey I (2006) Unravelling the conundrum of tannins in animal nutrition and health. *Journal of the Science of Food and Agriculture* **86**, 2010–2037. doi:10.1002/jsfa.2577
Muir SK, Kennedy AJ, Kearney G, Hutton P, Thompson AN, Vercoe P, Hill J (2020) Offering subterranean clover can reduce methane emissions compared with perennial ryegrass pastures during late spring and summer in sheep. *Animal Production Science* **60**, 1449–1458. doi:10.1071/AN18624
Nair RM, Hughes SJ, Peck DM, Crocker G, Ellwood S, Hill JR, Hunt CH, Auricht GC (2006) Progress in development of spotted medics (*Medicago arabica* L. Huds.) for Mediterranean farming systems. *Australian Journal of Agricultural Research* **57**, 447–455. doi:10.1071/AR05269
Nichols PGH, Loi A, Nutt BJ, Evans PM, Craig AD, Pengelly BC, Dear BS, Lloyd DL, Revell CK, Nair RM, Ewing MA, Howieson JG, Auricht GA, Howie JH, Sandral GA, Carr SJ, de Koning CT, Hackney BF, Crocker GJ, Snowball R, Hughes SJ, Hall EJ, Foster KJ, Skinner PW, Barbetti MJ, You MP (2007) New annual and short-lived perennial pasture legumes for Australian agriculture – 15 years of revolution. *Field Crops Research* **104**, 10–23. doi:10.1016/j.fcr.2007.03.016
Nichols PGH, Revell CK, Humphries AW, Howie JH, Hall EJ, Sandral GA, Ghamkhar K, Harris CA (2012) Temperate pasture legumes in

Australia – their history, current use, and future prospects. *Crop & Pasture Science* **63**, 691–725. doi:10.1071/CP12194

Nichols PGH, Foster KJ, Piano E, Pecetti L, Kaur P, Ghamkhar K, Collins WJ (2013) Genetic improvement of subterranean clover (*Trifolium subterraneum* L.). 1. Germplasm, traits and future prospects. *Crop & Pasture Science* **64**, 312–346. doi:10.1071/CP13118

Niderkorn V, Baumont R, Le Morvan A, Macheboeuf D (2011) Occurrence of associative effects between grasses and legumes in binary mixtures on *in vitro* rumen fermentation characteristics. *Journal of Animal Science* **89**, 1138–1145. doi:10.2527/jas.2010-2819

Niderkorn V, Martin C, Le Morvan A, Rochette Y, Awad M, Baumont R (2017) Associative effects between fresh perennial ryegrass and white clover on dynamics of intake and digestion in sheep. *Grass and Forage Science* **72**, 691–699. doi:10.1111/gfs.12270

Niderkorn V, Martin C, Bernard M, Le Morvan A, Rochette Y, Baumont R (2019) Effect of increasing the proportion of chicory in forage-based diets on intake and digestion by sheep. *Animal* **13**, 718–726. doi:10.1017/S1751731118002185

NSW DPI (2017) Lotus – greater lotus. Available at https://www.dpi.nsw.gov.au/agriculture/pastures-and-rangelands/species-varieties/pf/factsheets/lotus—greater-lotus. [Accessed 30 August 2022]

Nutt BJ, Harrison RJ, McComb JA, Howieson JG (2021) The breeding system of *Ornithopus sativus* Brot. subsp. *sativus*. *Grass and Forage Science* **76**, 3–9. doi:10.1111/gfs.12521

Oram RN (1990) 'Register of Australian herbage plant cultivars.' 3rd edn. (CSIRO Division of Plant Industries: Canberra, ACT)

Patra A, Park T, Kim M, Yu Z (2017) Rumen methanogens and mitigation of methane emission by anti-methanogenic compounds and substances. *Journal of Animal Science and Biotechnology* **8**, 13. doi:10.1186/s40104-017-0145-9

Pavao-Zuckerman MA, Waller JC, Ingle T, Fribourg HA (1999) Methane emissions of beef cattle grazing tall fescue pastures at three levels of endophyte infestation. *Journal of Environmental Quality* **28**, 1963–1969. doi:10.2134/jeq1999.00472425002800060036x

Pazos-Navarro M, Castello M, Bennett RG, Nichols P, Croser J (2017) *In vitro*-assisted single-seed descent for breeding-cycle compression in subterranean clover (*Trifolium subterraneum* L.). *Crop & Pasture Science* **68**, 958–966. doi:10.1071/CP17067

Pecetti L, Biazzi E, Tava A (2010) Variation in saponin content during the growing season of spotted medic [*Medicago arabica* (L.) Huds.]. *Journal of the Science of Food and Agriculture* **90**, 2405–2410. doi:10.1002/jsfa.4099

Pinares-Patiño CS, Ulyatt MJ, Waghorn GC, Lassey KR, Barry TN, Holmes CW, Johnson DE (2003) Methane emission by alpaca and sheep fed on lucerne hay or grazed on pastures of perennial ryegrass/white clover or birdsfoot trefoil. *The Journal of Agricultural Science* **140**, 215–226. doi:10.1017/S002185960300306X

Pirhofer-Walzl K, Soegaard K, Hogh-Jensen H, Eriksen J, Sanderson MA, Rasmussen J, Rasmussen J (2011) Forage herbs improve mineral composition of grassland herbage. *Grass and Forage Science* **66**, 415–423. doi:10.1111/j.1365-2494.2011.00799.x

Powell AM, Kemp PD, Jaya ID, Osborne MA (2007) Establishment, growth and development of plantain and chicory under grazing. *Proceedings of the New Zealand Grassland Association* **69**, 41–45. doi:10.33584/jnzg.2007.69.2684

Prusty S, Mohini M, Kundu SS, Kumar A, Datt C (2014) Methane emissions from river buffaloes fed on green fodders in relation to the nutriet intake and digestibility. *Tropical Animal Health and Production* **46**, 65–70. doi:10.1007/s11250-013-0447-7

Purcell PJ, Grant J, Boland TM, Grogan D, O'Kiely P (2012) The *in vitro* rumen methane output of perennial grass species and white clover varieties, and associative effects for their binary mixtures, evaluated using a batch-culture technique. *Animal Production Science* **52**, 1077–1088. doi:10.1071/AN12040

Ramirez-Restrepo CA, Barry TN (2005) Alternative temperate forages containing secondary compounds for improving sustainable productivity in grazing ruminants. *Animal Feed Science and Technology* **120**, 179–201. doi:10.1016/j.anifeedsci.2005.01.015

Real D, Warden J, Sandral GA, Colmer TD (2008) Waterlogging tolerance and recovery of 10 *Lotus* species. *Australian Journal of Experimental Agriculture* **48**, 480–487. doi:10.1071/EA07110

Reed KFM, Flinn PC (1993) Assessment of perennial legumes for acid soils in south western Victoria. In 'Alternative pasture legumes 1993'. Technical Report 219. (Eds DL Michalk, AD Craig, WJ Collins) pp. 152–154. (Primary Industries South Australia: Adelaide, SA)

Reed KFM, Nie ZN, Miller S, Hackney BF, Boschma SP, Mitchell ML, Albertsen TO, Moore GA, Clark SG, Craig AD, Kearney G, Li GD, Dear BS (2008) Field evaluation of perennial grasses and herbs in southern Australia. 1. Establishment and herbage production. *Australian Journal of Experimental Agriculture* **48**, 409–423. doi:10.1071/EA07135

Reisinger A, Clark H, Cowie AL, Emmet-Booth J, Gonzalez Fischer C, Herrero M, Howden M, Leahy S (2021) How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **379**, 20200452. doi:10.1098/rsta.2020.0452

Revell C, Thomas D (2004) Management of crop weeds through the strategic use of annual pasture. In 'Weed management: balancing people, planet, profit. Proceedings of the 14th Australian weeds conference'. (Eds BM Sindel, SB Johnson) (Weed Society of New South Wales: Sydney) [Accessed 30 August 2022]

Robertson M (2006) Lucerne prospects : drivers for widespread adoption of lucerne for profit and salinity management. Available at https://nla.gov.au/nla.cat-vn3889872 [Accessed 30 August 2022]

Roldan MB, Cousins G, Muetzel S, Zeller WE, Fraser K, Salminen J-P, Blanc A, Kaur R, Richardson K, Maher D, Jahufer Z, Woodfield DR, Caradus JR, Voisey CR (2022) Condensed tannins in white clover (*Trifolium repens*) foliar tissues expressing the transcription factor TaMYB14-1 bind to forage protein and reduce ammonia and methane emissions *in vitro*. *Frontiers in Plant Science* **12**, 777354. doi:10.3389/fpls.2021.777354

Rumball W (1982) Plant introduction trials: performance of sainfoin (*Onobrychis viciifolia* Scop.) and related species at Palmerston North. *New Zealand Journal of Experimental Agriculture* **10**, 383–385. doi:10.1080/03015521.1982.10427903

Rumball W (1986) Grasslands Puna' chicory (*Cichorium intybus* L.). *New Zealand Journal of Experimental Agriculture* **14**, 105–107 doi:10.1080/03015521.1986.10426133

Sanderson MA, Labreveux M, Hall MH, Elwinger GF (2003) Forage yield and persistence of chicory and English plantain. *Crop Science* **43**, 995–1000. doi:10.2135/cropsci2003.9950

Sandral GA, Price A, Hildebrand SM, Fuller CG, Haling RE, Stefanski A, Yang Z, Culvenor RA, Ryan MH, Kidd DR, Diffey S, Lambers H, Simpson RJ (2019) Field benchmarking of the critical external phosphorus requirements of pasture legumes for southern Australia. *Crop & Pasture Science* **70**, 1080–1096. doi:10.1071/CP19014

Schachtman DP, Kelman WM (1991) Potential of *Lotus* germplasm for the development of salt, aluminium and manganese tolerant pasture plants. *Australian Journal of Agricultural Research* **42**, 139–149. doi:10.1071/AR9910139

Scharenberg A, Arrigo Y, Gutzwiller A, Soliva CR, Wyss U, Kreuzer M, Dohme F (2007) Palatability in sheep and *in vitro* nutritional value of dried and ensiled sainfoin (*Onobrychis viciifolia*) birdsfoot trefoil (*Lotus corniculatus*), and chicory (*Cichorium intybus*). *Archives of Animal Nutrition* **61**, 481–496. doi:10.1080/17450390701664355

Searchinger TD, Wirsenius S, Beringer T, Dumas P (2018) Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249–253. doi:10.1038/s41586-018-0757-z

Siah SD, Konczak I, Agboola S, Wood JA, Blanchard CL (2012) *In vitro* investigations of the potential health benefits of Australian-grown faba beans (*Vicia faba* L.): chemopreventative capacity and inhibitory effects on the angiotensin-converting enzyme, α-glucosidase and lipase. *British Journal of Nutrition* **108**, S123–S134. doi:10.1017/S0007114512000803

Simmons AT, Cowie AL, Brock PM (2020) Climate change mitigation for Australian wheat production. *Science of The Total Environment* **725**, 138260. doi:10.1016/j.scitotenv.2020.138260

Singh S, Kushwaha BP, Nag SK, Mishra AK, Singh A, Anele UY (2012) *In vitro* ruminal fermentation, protein and carbohydrate fractionation, methane production and prediction of twelve commonly used Indian green forages. *Animal Feed Science and Technology* **178**, 2–11. doi:10.1016/j.anifeedsci.2012.08.019

Smith LG, Kirk GJD, Jones PJ, Williams AG (2019) The greenhouse gas impacts of converting food production in England and Wales to organic methods. *Nature Communications* **10**, 4641. doi:10.1038/s41467-019-12622-7

Soder KJ, Gregorini P, Scaglia G, Rook AJ (2009) Dietary selection by domestic grazing ruminants in temperate pastures: current state of knowledge, methodologies, and future direction. *Rangeland Ecology & Management* **62**, 389–398. doi:10.2111/08-068.1

Sun XZ, Hoskin SO, Muetzel S, Molano G, Clark H (2011) Effects of forage chicory (*Cichorium intybus*) and perennial ryegrass (*Lolium perenne*) on methane emissions *in vitro* and from sheep. *Animal Feed Science and Technology* **166-167**, 391–397. doi:10.1016/j.anifeedsci.2011.04.027

Sun XZ, Hoskin SO, Zhang GG, Molano G, Muetzel S, Pinares-Patiño CS, Clark H, Pacheco D (2012) Sheep fed forage chicory (*Cichorium intybus*) or perennial ryegrass (*Lolium perenne*) have similar methane emissions. *Animal Feed Science and Technology* **172**, 217–225. doi:10.1016/j.anifeedsci.2011.11.007

Suybeng B, Mwangi FW, McSweeney CS, Charmley E, Gardiner CP, Malau-Aduli BS, Malau-Aduli AEO (2021) Response to climate change: evaluation of methane emissions in northern Australian beef cattle on a high quality diet supplemented with desmanthus using open-circuit respiration chambers and greenfeed emission monitoring systems. *Biology* **10**, 943. doi:10.3390/biology10090943

Swinny E, Revell CK, Campbell N, Spadek E, Russo C (2015) In search of photosensitising compounds in the annual forage legume *Biserrula pelecinus* L. *Crop & Pasture Science* **66**, 1161–1166. doi:10.1071/CP14342

Szumacher-Strabel M, Stochmal A, Cieslak A, Kozłowska M, Kuznicki D, Kowalczyk M, Oleszek W (2019) Structural and quantitative changes of saponins in fresh alfalfa compared to alfalfa silage. *Journal of the Science of Food and Agriculture* **99**, 2243–2250. doi:10.1002/jsfa.9419

Tava A, Pecetti L (2012) Chemical investigation of saponins from twelve annual *Medicago* species and their bioassay with the brine shrimp *Artemia salina*. *Natural Product Communications* **7**, 837–840. doi:10.1177/1934578X1200700708

Tava A, Biazzi E, Ronga D, Pecetti L, Avato P (2022) Biologically active compounds from forage plants. *Phytochemistry Reviews* **21**, 471–501. doi:10.1007/s11101-021-09779-9

Thomas DT, Milton JTB, Revell CK, Ewing MA, Lindsay DR (2015) Individual and socially learned preferences for biserrula (*Biserrula pelecinus* L.) in sheep. *Grass and Forage Science* **70**, 374–380. doi:10.1111/gfs.12108

Thomas DT, Beletse YG, Dominik S, Lehnert SA (2021) Net protein contribution and enteric methane production of pasture and grain-finished beef cattle supply chains. *Animal* **15**, 100392. doi:10.1016/j.animal.2021.100392

United Nations (2017) World population prospects: the 2017 revision, key findings and advance tables. Available at https://population.un.org/wpp/publications/files/wpp2017_keyfindings.pdf [Accessed 30 August 2022]

Vargas JJ, Pabón ML, Carulla JE (2018) Methane production from four forages at three maturity stages in a ruminal *in vitro* system. *Revista Colombiana De Ciencias Pecuarias* **31**, 120–129. doi:10.17533/udea.rccp.v31n2a05

Vasta V, Daghio M, Cappucci A, Buccioni A, Serra A, Viti C, Mele M (2019) Invited review: Plant polyphenols and rumen microbiota responsible for fatty acid biohydrogenation, fiber digestion, and methane emission: experimental evidence and methodological approaches. *Journal of Dairy Science* **102**, 3781–3804. doi:10.3168/jds.2018-14985

Vercoe P (2016) Innovative livestock systems to adapt to climate change and reduce emissions. Available at https://www.mla.com.au/contentassets/e67a06e15628430eb349e9e66900fcd8/b.cch.7510_final_report.pdf [Accessed 30 August 2022]

Waghorn G (2008) Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production – progress and challenges. *Animal Feed Science and Technology* **147**, 116–139. doi:10.1016/j.anifeedsci.2007.09.013

Waghorn GC, Tavendale MH, Woodfield DR (2002) Methanogenesis from forages fed to sheep. *Proceedings of the New Zealand Grassland Association* **64**, 167–171. doi:10.33584/jnzg.2002.64.2462

Waters C, Cowie A, Wang B, Simpson M, Gray J, Simmons A, Stephens S (2020) Abatement opportunities from the agricultural sector in New South Wales. Modelling to support the development of the primary industries productivity and abatement program. (NSW Department of Primary Industries) Available at https://nla.gov.au/nla.obj-3092213693/view [Accessed 30 August 2022]

Watson A, Ghosh S, Williams MJ, Cuddy WS, Simmonds J, Rey M-D, Asyraf Md Hatta M, Hinchliffe A, Steed A, Reynolds D, Adamski NM, Breakspear A, Korolev A, Rayner T, Dixon LE, Riaz A, Martin W, Ryan M, Edwards D, Batley J, Raman H, Carter J, Rogers C, Domoney C, Moore G, Harwood W, Nicholson P, Dieters MJ, DeLacy IH, Zhou J, Uauy C, Boden SA, Park RF, Wulff BBH, Hickey LT (2018) Speed breeding is a powerful tool to accelerate crop research and breeding. *Nature Plants* **4**, 23–29. doi:10.1038/s41477-017-0083-8

Wilson RL, Bionaz M, MacAdam JW, Beauchemin KA, Naumann HD, Ates S (2020) Milk production, nitrogen utilization, and methane emissions of dairy cows grazing grass, forb, and legume-based pastures. *Journal of Animal Science* **98**, skaa220. doi:10.1093/jas/skaa220

Data availability. The data used in this paper is all from previously published research. The publications are referenced in tables and text where data have been presented.

Conflicts of interest. The authors declare no conflicts of interest.

Declaration of funding. We acknowledge funding from Meat and Livestock Australia (MLA), the Australian Government Department of Industry, Science and Resources and partnering organisation in the 'P.PSH.1333 – Delivering Integrated Management System (IMS) options for CN30' and from MLA and NSW Department of Primary Industries for the 'P.PSH.2013 – Low methane emission pastures and increased red meat production to achieve CN30' that have co-funded the preparation of this paper.

Acknowledgements. We would like to thank John Piltz and Peter Grace for their input to the concepts developed in the paper. We thank Kathryn Egerton-Warburton and Mark Evans for their comments on the manuscript.

Author affiliations

[A]NSW Department of Primary Industries, Orange Agricultural Institute, 1447 Forest Road, Orange, NSW 2800, Australia.

[B]NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, Pine Gully Road, Wagga Wagga, NSW 2650, Australia.

[C]NSW Department of Primary Industries, 98 Victoria Street, Taree, NSW 2430, Australia.

[D]NSW Department of Primary Industries, Tamworth Agricultural Institute, 4 Marsden Park Road, Calala, NSW 2340, Australia.

[E]Mt Pleasant Laboratories, Tasmanian Institute of Agriculture, 165 Westbury Road, Prospect, Tas. 7250, Australia.

[F]Australian Pastures Genebank, South Australian Research and Development Institute, Urrbrae, SA 5064, Australia.

[G]NSW Department of Primary Industries, 28 Morisset Street, Queanbeyan, NSW 2620, Australia.

[H]UWA School of Agriculture and Environment and UWA Institute of Agriculture, The University of Western, Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.

[I]NSW Department of Primary Industries/University of New England, Trevenna Road, Armidale, NSW 2351, Australia.

[J]Department of Primary Industries and Regions, Government of South Australia, 74 Struan House Road, Naracoorte, SA 5271, Australia.

[K]Faculty of Veterinary and Agricultural Sciences, University of Melbourne, Parkville, Vic. 3010, Australia.