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Greenhouse gas implications of leucaena-based pastures. Can we develop an emissions reduction methodology for the beef industry? *¿Podemos desarrollar una metodología para la reducción de las emisiones de gases de efecto invernadero para pasturas con leucaena?*

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Abstract

The perennial legume leucaena (*Leucaena leucocephala*) is grown across the subtropics for a variety of purposes including livestock fodder. Livestock in Australia emit a significant proportion of the methane produced by the agriculture sector and there is increasing pressure to decrease emissions from beef cattle production systems. In addition to direct productivity gains for livestock, leucaena has been shown to lower enteric methane production, suggesting an opportunity for emissions mitigation and Commonwealth Emissions Reduction Fund (ERF) methodology development, where leucaena browse is adopted for high value beef production. Determining the proportion of leucaena in the diet may be one of the more challenging aspects in attributing mitigation. Current enteric emission relationships for cattle consuming mixed grass-leucaena diets are based on intensive respiration chamber work. Herd-scale methane flux has also been determined using open path laser methodologies and may be used to validate an on-farm herd-scale methodology for leucaena feeding systems. The methodology should also address increased potential for soil organic carbon storage by leucaena grazing systems, and changes in nitrous oxide production. This paper outlines the background, justification, eligibility requirements and potential gaps in research for an emissions quantification protocol that will lead to the adoption of a leucaena methodology by the Australian beef industry. Development of a methodology would be supported by research conducted in Australia.

Keywords: CO₂ mitigation, cattle, grazing, methane, modelling, nitrous oxide, ruminants.

Resumen

La leguminosa perenne leucaena (*Leucaena leucocephala*) se cultiva a lo largo del subtrópico para una variedad de propósitos, incluido el forraje para el ganado. El ganado en Australia genera una proporción significativa del metano producido por el sector agrícola y existe una presión creciente para reducir las emisiones procedentes de los sistemas de producción de ganado de carne. Además de las ganancias directas en la productividad ganadera, se ha demostrado que leucaena reduce la producción de metano entérico. Esto sugiere una oportunidad para la mitigación de emisiones y el desarrollo de metodologías en el marco del Commonwealth Emissions Reduction Fund (ERF), adoptando tecnologías de leucaena para la producción de carne de res de alto valor. Determinar su proporción en la dieta animal es posiblemente uno de los desafíos más importantes para cuantificar la contribución de la leucaena a la mitigación de las emisiones. Los conocimientos actuales relacionados con las emisiones de metano por el ganado que consume dietas mixtas de gramíneas con leucaena, se basan en trabajos intensivos en cámaras respiratorias. Para medir el flujo de metano a escala de rebaño

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existen metodologías láser (OP-FTIR laser) con las que se pueden validar metodologías a nivel de sistemas de producción que incluyen leucaena como alimento. La metodología también debería considerar el potencial de sistemas de pastoreo con leucaena tanto para la acumulación de carbono orgánico en el suelo como para cambios en la producción de óxido nítrico. Este documento resume los antecedentes, la justificación, los requisitos para la elegibilidad y las necesidades de investigación para un protocolo de cuantificación de emisiones que llevará a la adopción de una metodología de leucaena por parte de la industria australiana de carne bovina. El desarrollo de esta metodología se apoyaría principalmente en investigaciones realizadas en el pasado en Australia.

Palabras clave: Ganado, metano, mitigación de CO₂, modelación, óxido nítrico, pastoreo, rumiantes.

Introduction

The perennial leguminous shrub leucaena (*Leucaena leucocephala*) is grown across the tropical and subtropical regions of South/Southeast Asia and northern Australia for livestock fodder, nitrogen fixation, firewood and paper pulp (Shelton and Brewbaker 1994). In Australia, the shrub can be incorporated in grass pastures for beef cattle, providing liveweight gains superior to those from most other legume-grass pastures and comparable with feedlot finishing. Across Queensland, approximately 125,000 ha has been identified by satellite imagery as dedicated to leucaena pastures (Beutel et al. 2018). Recent research has demonstrated additional benefits in the form of potential reduction of enteric methane production and increased soil carbon (C) storage, implying that the shrub may also reduce greenhouse gas (GHG) emissions at the farm level (McSweeney and Tomkins 2015; Harrison et al. 2015; Vercoe 2015; Conrad et al. 2017). This presents an emissions-mitigation opportunity that would apply across the industry where leucaena is managed. To reduce the carbon footprint of the Australian beef industry, particularly for northern bioregions where emissions per livestock unit are typically higher than for southern cattle (Charmley et al. 2008), there is justification for developing an ‘emissions-reduction methodology’ based on leucaena. A proposed methodology is supported by research conducted under the National Livestock Methane Program (MLA 2015a), modelling work undertaken under the Whole Farm Systems Abatement Modelling program (WFM 2017) and a series of independent studies.

This paper outlines the background, justification, eligibility requirements and potential gaps in research for an emissions-quantification protocol that will lead to the adoption of a methodology. A methodology would recognize reduced methane emissions by animals grazing leucaena.

Emissions-reduction potential and attribution

Approximately 16% of Australia's greenhouse gas (CO₂-eq) emissions come from agriculture, with 65% of

this emitted by ruminants as methane. Cattle are responsible for about 70% of the enteric methane produced (Commonwealth of Australia 2014) and there are increasing efforts to decrease intensity of emissions from the livestock sector (MLA 2015b). A number of plants, plant products and plant secondary compound fractions have been demonstrated to have potential to reduce enteric methanogenesis (Vercoe 2015) when consumed by ruminants. The main compounds in leucaena that confer antimethanogenic effects in vitro and in vivo include phenolic compounds such as condensed tannins and flavanol glycosides (Kennedy and Charmley 2012; Vercoe 2015; McSweeney and Tomkins 2015).

Kennedy and Charmley (2012) demonstrated that the level of readily fermentable crude protein (RFCP) in legumes can be negatively correlated with methane production. Whether this indicates the operation of hydrogen (H) sinks associated with the RFCP fraction is uncertain, but it does indicate a need to incorporate a factor such as legume content of the diet in predictive equations for methane production, especially where plants such as leucaena are a significant proportion of the diet. Determining the proportion of leucaena in the diet would be one of the more challenging aspects in attributing methane mitigation. Current options to estimate grass:legume proportion in the diet include the use of faecal NIRS methodologies and $\delta^{13}\text{C}$ ratios (Coates and Dixon 2007).

If the legume content of the diet of the northern beef herd could be accounted for, then estimates of aggregate herd emissions may be reduced by around 30% (Kennedy and Charmley 2012). In addition, growth rates of cattle grazing leucaena-Rhodes grass (*Chloris gayana*) pastures are substantially higher and methane production commensurately lower than those of cattle grazing a Rhodes grass-dominated pasture (Harrison et al. 2015), particularly when leucaena is irrigated (Taylor et al. 2016).

A proposed methodology may be specific to a production system as defined by herd composition (class, age, live weight), where leucaena is used to finish steers

to a target live weight or support breeding animals during periods of low pasture availability. The duration of leucaena feeding and intake or proportion of the diet will also be critical in revising the Herd Management Calculator (<http://bit.ly/2SZf2qI>).

Increased soil carbon storage opportunities

Incorporating leucaena into a grass grazing system increases biomass production ([Radrizzani et al. 2016](#)) and C inputs to soil, which leads to increasing organic C storage, especially in N-depleted soils. Conrad et al. ([2017](#)) estimated that a leucaena-buffel grass grazing system had an increase in soil C storage of 280 kg C/ha/yr in the top 30 cm of a Vertisol soil over a 40-year period. This equates to 1.03 t CO₂-eq/ha/yr with 50% of this C incorporated in the top 15 cm horizon ([Radrizzani et al. 2011](#)). This increase in C storage occurs primarily from the increased C inputs from biomass increase due to symbiotic N₂ fixation, which can account for up to 36 kg N/ha/yr in the soil ([Resh et al. 2002](#); [Conrad et al. 2018](#)). Increased grass yield, C inputs, humus formation, slowing C decomposition and providing for increase in C storage become co-benefits for leucaena-based pastures ([Kopittke et al. 2018](#)). However, the increase in soil C storage in leucaena-grass grazing systems may be limited due to nutrient deficiencies of P and S, which occur frequently in Australia ([Radrizzani et al. 2016](#)), indicating that periodic application of nutrients other than N may be beneficial to increased soil C storage.

Mineralization of leucaena-N₂ fixed organic N produces nitrate-N and NO₃⁻ and results in nitrous oxide (N₂O) and di-nitrogen (N₂) production. Nitrous oxide is a potent GHG, with a global warming potential of 296 CO₂-eq on a 100-year time horizon ([Dalal et al. 2003](#); [EPA 2018](#)). It is possible that N₂O emissions from soil supporting a leucaena-grass pasture may partially negate the positive impact of increase in soil C storage on GHG mitigation. Quantitative estimates of N₂O emissions from a leucaena-grass pasture system are scarce. It is likely that the nitrate-N level in soil remains relatively low due to the uptake by grasses, thereby minimizing N₂O production ([Conrad et al. 2017](#)).

Rumen microbial structure and function of leucaena-fed cattle

Understanding effects of leucaena on rumen microbial populations is an important factor in developing an emissions methodology. Analyses of rumen metabolism have indicated that leucaena-fed steers had an increased supply of amino acids and soluble carbohydrates,

resulting in an apparent increase in microbial protein synthesis and a sink for metabolic H ([McSweeney and Tomkins 2015](#)). In addition, a shift in fermentation from acetate to longer chain fatty acids has been reported and can be expected to result in greater energy capture for the animal.

DNA sequencing of the rumen microbiota has demonstrated a consistent difference in the diversity of methanogens in cattle foraging leucaena-grass systems compared with grass pastures for both irrigated and dryland systems ([McSweeney and Tomkins 2015](#)). The relative abundance of *Methanospaera* spp. alone as a proportion of the total methanogen population was higher in leucaena-fed animals and may be responsible for differences in methane emissions. *Methanospaera* spp. have been previously reported to be enriched in 'low methane' emitting ruminants ([Shi et al. 2014](#)). Analyses at the bacterial family level have shown that some species belonging to Lachnospiraceae, Prevotellaceae, Spirochaetaceae, Desulfovibrionaceae, Ruminococcaceae, Bacteroidaceae and Veillonellaceae increased significantly in cattle grazing leucaena, while other species belonging to Erysipelotrichaceae and also Prevotellaceae and Bacteroidaceae decreased significantly relative to pasture-fed cattle ([McSweeney and Tomkins 2015](#)). This indicates a specific response to leucaena in the diet. It is likely that the shift in bacterial populations and metabolism associated with the presence of leucaena results in less metabolic H being produced for hydrogenotrophic methanogens because microbial protein and longer chain fatty acids become sinks for H. These shifts in the bacterial and methanogen populations are the likely basis for alterations in methanogenesis in leucaena-fed cattle.

Modelling whole-farm impacts on production, profitability and net emissions

Modelling of leucaena-based production systems can provide estimates of impacts on farm profitability of changes in liveweight gain (LWG), increase in soil C storage, methane emissions and urinary nitrogen concentration. To compute GHG emissions on a whole-farm basis, herd numbers and age/class structures can be used in static GHG emissions calculators, such as the Beef-Greenhouse Accounting Framework (B-GAF) (Doran-Browne and Eckard 2018). The diversified emissions profiles encompassed by B-GAF are essential for estimating whole-farm emissions from leucaena systems. Alternatives to static tools for estimating steady-state herd structures and GHG emissions include APSIM ([Keating et al. 2003](#)). APSIM can simulate temporal changes, which static models do not. Inclusion of a leucaena module in a dynamic farming system model such as APSIM would allow further investigation of

how leucaena growth and defoliation through grazing influence LWG and profitability.

Measurements of the nutritional value of leucaena and potential to increase soil C storage at depth are required for model parameterization. The nutritive value of leucaena ([Bassala et al. 1991](#); [Agbede and Aletor 2004](#)) and effects on LWG ([Shelton and Brewbaker 1994](#); [Harrison et al. 2016](#)) have been well described. Few experiments simultaneously measure leucaena nutritive value, LWG, increase in soil organic C storage and GHG emissions, although these data are critical for parameterizing and developing model formulae for leucaena grazing systems.

Since leucaena generally provides more available forage than comparable pasture grasses, higher stocking rates are sustainable, but this results in greater total emissions per unit area ([Harrison et al. 2016](#)). Model-specific metrics are required to standardize comparisons. [Harrison et al. \(2015\)](#) described the comparison between 3 leucaena grazing scenarios and a baseline scenario in terms of: 1) average annual stocking rates; 2) total LW production; and 3) net farm emissions. To maintain the same average annual stocking rate or LW production, Scenarios 1 and 2 carried 5 or 12% fewer cattle than the baseline because animals on leucaena grew faster and had greater mean LW. In contrast, the number of animals carried and LW production in Scenario 3 increased by 15 and 31% relative to the baseline, respectively, due to enteric methane abatement and greater LWG of animals grazing leucaena. In all scenarios, emissions intensity (net farm emissions per unit LW sold) was reduced by more than 23% relative to baseline emissions. Other modelling studies incorporating leucaena have demonstrated that: reducing the ratio of breeding cows relative to steers and unmated heifers; higher female fecundity; and earlier joining of maiden heifers, were conducive to increased profitability ([Harrison et al. 2016](#)), but only higher fecundity and/or early joining of maiden heifers resulted in lower emissions per unit of live weight, especially when combined with existing interventions.

Although calibration data are required for reliable parameterization, models can contrast various scenarios with baseline systems, or simulate long-term implications of climate change on whole-farm emissions intensities. Future modelling aspects for leucaena could develop more dynamic biophysical models that incorporate livestock rotations between paddocks and seasonal climatic effects on leucaena growth and emissions from the grazing system.

Methodology development, validation and limitations

Any methodology has to be cost-effective to implement and readily verifiable. A leucaena methodology will need

to account for methane and nitrous oxide emissions and soil C components. These components of a methodology will need to be measured or estimated from models. A methodology for measuring reductions in GHG emissions by grazing cattle on leucaena-based pastures has potential to complement the existing Beef Cattle Herd Management methodology ([Commonwealth of Australia 2015](#)), which captures reductions in emissions through increasing LWG and earlier turnoff achieved by cattle provided with supplementary feed (including improved pastures). While the current Beef Cattle Herd Management method quantifies the reduction in lifetime emissions through earlier turnoff, a method proposed specifically for leucaena would target: direct reduction in enteric methane emissions caused by leucaena in the diet of grazing cattle; increase in soil C storage; and losses from N₂O.

The current emissions relationship is based on respiration chamber work ([Kennedy and Charmley 2012](#)) and is the basis for estimating emissions from cattle consuming grass-leucaena diets. Herd-scale methodologies are available for validation on-farm based on methane flux determination using open path, OP-FTIR laser technologies ([Jones et al. 2011](#); [Tomkins and Charmley 2015](#); [Phillips et al. 2016](#)) or eddy covariance methods. The use of the SF₆ tracer technique or Greenfeed system (C-Lock Inc., Rapid City, SD, USA) could also be applied in the field and offer an alternative approach to quantify individual methane production data ([Arbre et al. 2015](#)). These techniques provide a measure of emissions relativity and are currently the only on-farm non-invasive methods available to corroborate the effects of leucaena inclusion in pasture on enteric methane emissions for grazing cattle.

Conclusions

Research and modelling, that have been reported under the National Livestock Methane Program, the Whole Farm Systems Abatement Modelling program and previous and ongoing independent studies, provide justification to expand methodology opportunities. This is particularly relevant for those parts of Australia's beef industry, where leucaena feeding systems are adopted. In addition to the benefits associated with livestock production gains and efficiencies, the co-benefits in increasing soil C storage, humus formation and pasture improvement are well documented. Advances in methodologies to measure methane flux on-farm at a herd scale and analyses of rumen metabolism at the individual animal scale are sufficiently advanced to validate a methodology based on leucaena feeding. Future

modelling must develop more dynamic biophysical models for leucaena systems, incorporating livestock rotations between paddocks and seasonal climatic effects on pasture growth and farm-scale emissions, which will further validate the development, adoption and practical application of a leucaena methodology for the Australian beef industry.

References

(Note of the editors: All hyperlinks were verified 1 August 2019.)

- Agbede JO; Aletor VA. 2004. Chemical characterization and protein quality evaluation of leaf protein concentrates from *Glyricidia sepium* and *Leucaena leucocephala*. *International Journal of Food Science and Technology* 39:253–261. doi: [10.1111/j.1365-2621.2004.00779.x](https://doi.org/10.1111/j.1365-2621.2004.00779.x)
- Arbre M; Rochette Y; Guyader J; Lascoux C; Gamez LM; Eugène M; Morgavi DP; Renand G; Doreau M; Martin C. 2015. Repeatability of enteric methane determinations from cattle using either the SF₆ tracer technique or the GreenFeed system. *Animal Production Science* 56:238–243. doi: [10.1071/AN15512](https://doi.org/10.1071/AN15512)
- Bassala P; Felker P; Swakon DHD. 1991. A comparison of *Leucaena leucocephala* and *Leucaena pulverulenta* leaf and stem age classes for nutritional value. *Tropical Grasslands* 25:313–316. [bit.ly/2T2aNe7](https://doi.org/10.1071/2T2aNe7)
- Beutel TS; Corbet DH; Hoffmann MB; Buck SR; Kienzle M. 2018. Quantifying leucaena cultivation extent on grazing land. *The Rangeland Journal* 40:31–38. doi: [10.1071/RJ17085](https://doi.org/10.1071/RJ17085)
- Charmley E; Stephens ML; Kennedy PM. 2008. Predicting livestock productivity and methane emissions in northern Australia: Development of a bio-economic modelling approach. *Australian Journal of Experimental Agriculture* 48:109–113. doi: [10.1071/EA07264](https://doi.org/10.1071/EA07264)
- Coates DB; Dixon RM. 2007. Faecal near infrared reflectance spectroscopy (F.NIRS) measurements of non-grass proportions in the diet of cattle grazing tropical rangelands. *The Rangeland Journal* 29:51–63. doi: [10.1071/RJ07011](https://doi.org/10.1071/RJ07011)
- Commonwealth of Australia. 2014. Australian National Greenhouse Accounts: National Inventory Report 2012. Volume 2. Department of the Environment, Canberra, ACT, Australia. [bit.ly/2YCMHvN](https://doi.org/10.1071/2YCMHvN)
- Commonwealth of Australia. 2015. Carbon credits (Carbon Farming Initiative – Beef Cattle Herd Management) methodology determination 2015. Department of the Environment, Canberra, ACT, Australia. [bit.ly/2LX2rni](https://doi.org/10.1071/2LX2rni)
- Conrad KA; Dalal RC; Dalzell SA; Allen DE; Menzies NW. 2017. The sequestration and turnover of soil organic carbon in subtropical leucaena-grass pastures. *Agriculture, Ecosystems and Environment* 248:38–47. doi: [10.1016/j.agee.2017.07.020](https://doi.org/10.1016/j.agee.2017.07.020)
- Conrad KA; Dalal RC; Dalzell SA; Allen DE; Fujinuma R; Menzies NW. 2018. Soil nitrogen status and turnover in subtropical leucaena-grass pastures as quantified by $\delta^{15}\text{N}$ natural abundance. *Geoderma* 313:126–134. doi: [10.1016/j.geoderma.2017.10.029](https://doi.org/10.1016/j.geoderma.2017.10.029)
- Dalal RC; Wang W; Robertson GP; Parton WJ. 2003. Nitrous oxide emission from Australian agricultural lands and mitigation options: A review. *Australian Journal of Soil Research* 41:165–195. doi: [10.1071/SR02064](https://doi.org/10.1071/SR02064)
- Doran-Browne NA; Eckard RJ (2018). A Greenhouse Accounting Framework for Beef properties (B-GAF) based on the Australian National Greenhouse Gas Inventory methodology. Updated May 2018. <http://bit.ly/2KjLGja>
- EPA (Environmental Protection Agency). 2018. Understanding global warming potentials. United States Environmental Protection Agency, Washington, DC, USA. [bit.ly/313TOCS](https://doi.org/10.1071/313TOCS)
- 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](https://doi.org/10.1016/j.agsy.2015.03.003)
- Harrison MT; Cullen BR; Tomkins NW; McSweeney C; Cohn P; Eckard RJ. 2016. The concordance between greenhouse gas emissions, livestock production and profitability of extensive beef farming systems. *Animal Production Science* 56:370–384. doi: [10.1071/AN15515](https://doi.org/10.1071/AN15515)
- Jones FM; Phillips FA; Naylor T; Mercer NB. 2011. Methane emissions from grazing Angus beef cows selected for divergent residual intake. *Animal Feed Science and Technology* 166/167:302–307. doi: [10.1016/j.anifeedsci.2011.04.020](https://doi.org/10.1016/j.anifeedsci.2011.04.020)
- Keating BA; Carberry PS; Hammer GL; Probert ME; Robertson MJ; Holzworth D; Huth NI; Hargreaves JN; Meinke H; Hochman Z; McLean G; Verberg K; Snow V; Dimes JP; Silburn M; Wang E; Brown S; Bristow KL; Asseng S; Chapman S; McCown RL; Freebairn DM; Smith CJ. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* 18:267–288. [10.1016/S1161-0301\(02\)00108-9](https://doi.org/10.1016/S1161-0301(02)00108-9)
- Kennedy P; Charmley E. 2012. Methane yields from Brahman cattle fed tropical grasses and legumes. *Animal Production Science* 52:225–239. doi: [10.1071/AN11103](https://doi.org/10.1071/AN11103)
- Kopittke PM; Hernandez-Soriano MC; Dalal RC; Finn D; Menzies NW; Hoeschen C; Mueller CW. 2018. Nitrogen-rich microbial products provide new organo-mineral interactions for the stabilization of soil organic matter. *Global Change Biology* 24:1762–1770. doi: [10.1111/gcb.14009](https://doi.org/10.1111/gcb.14009)
- McSweeney C; Tomkins N. 2015. Impacts of Leucaena plantations on greenhouse gas emissions in northern Australian cattle production systems. Final Report. Meat & Livestock Australia, Sydney, Australia. [bit.ly/2KfLxgy](https://doi.org/10.1071/2KfLxgy)
- MLA (Meat & Livestock Australia). 2015a. National Livestock Methane Program. Meat & Livestock Australia, Sydney, Australia. [bit.ly/2YB5ovK](https://doi.org/10.1071/2YB5ovK)
- MLA (Meat & Livestock Australia). 2015b. More meat, milk and wool: Less methane. Meat & Livestock Australia, Sydney, Australia. [bit.ly/2K943Zg](https://doi.org/10.1071/2K943Zg)
- Phillips FA; Wiedemann SG; Naylor TA; McGahan EJ; Warren BR; Murphy CM; Parkes S; Wilson J. 2016. Methane, nitrous oxide and ammonia emissions from pigs housed on litter and from stockpiling of spent litter. *Animal Production Science* 56:1390–1403. doi: [10.1071/AN15650](https://doi.org/10.1071/AN15650)

- Radrizzani A; Shelton HM; Dalzell SA; Kirchoff G. 2011. Soil organic carbon and total nitrogen under *Leucaena leucocephala* pastures in Queensland. *Crop and Pasture Science* 62:337–345. doi: [10.1071/CP10115](https://doi.org/10.1071/CP10115)
- Radrizzani A; Shelton HM; Kravchuk O; Dalzell SA. 2016. Survey of long-term productivity and nutritional status of *Leucaena leucocephala*-grass pastures in subtropical Queensland. *Animal Production Science* 56:2064–2073. doi: [10.1071/AN15084](https://doi.org/10.1071/AN15084)
- Resh S; Binkley D; Parrotta JA. 2002. Greater soil carbon sequestration under nitrogen-fixing trees compared with *Eucalyptus* species. *Ecosystems* 5:217–231. doi: [10.1007/s10021-001-0067-3](https://doi.org/10.1007/s10021-001-0067-3)
- Shelton H; Brewbaker J. 1994. *Leucaena leucocephala* – the most widely used forage tree legume. In: Gutteridge RC; Shelton HM, eds. 1994. Forage tree legumes in tropical agriculture. CAB International, Wallingford, UK. p. 15–29. bit.ly/2MzgQ94
- Shi W; Moon CD; Leahy SC; Kang D; Froula J; Kittelmann S; Fan C; Deutsch S; Gagic D; Seedorf H; Kelly WJ; Atua R; Sang C; Soni P; Li D; Pinares-Patiño CS; McEwan JC; Janssen PH; Chen F; Visel A; Wang Z; Attwood GT; Rubin EM. 2014. Methane yield phenotypes linked to differential gene expression in the sheep rumen microbiome. *Genome Research* 24:1517–1525. doi: [10.1101/gr.168245.113](https://doi.org/10.1101/gr.168245.113)
- Taylor CA; Harrison MT; Telfer M; Eckard R. 2016. Modelled greenhouse gas emissions from beef cattle grazing irrigated leucaena in northern Australia. *Animal Production Science* 56:594–604. doi: [10.1071/AN15575](https://doi.org/10.1071/AN15575)
- Tomkins NW; Charmley E. 2015. Herd-scale measurements of methane emissions from cattle grazing extensive subtropical grasslands using the open-path laser technique. *Animal* 9:2029–2038. doi: [10.1017/S1751731115001688](https://doi.org/10.1017/S1751731115001688)
- Vercoe P. 2015. The mechanism of antimethanogenic bioactivity of plants in the rumen. Final Report. Meat & Livestock Australia, Sydney, Australia. bit.ly/2YD5tPE
- WFM (Whole Farm Modelling). 2017. Whole farm systems modelling. Primary Industries Climate Challenges Centre, The University of Melbourne, Parkville, VIC, Australia. bit.ly/2OwlOWp

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