



EIP-AGRI Focus Group Reducing livestock emissions from Cattle farming

Mini-paper – Feeding strategies to reduce methane and ammonia emissions

Authors

David R. Yáñez-Ruiz, Diego Morgavi, Tom Misselbrook, Marcello Melle, Silvija Dreijere, Ole Aes, and Mateusz Sekowski.

Introduction

Beef and dairy cattle husbandry are one of the major sources of methane (greenhouse gas) and NH_3 (atmospheric pollutant) to the environment (IPCC, 2006). Ruminants are herbivores that have developed specialized forestomach (rumen), where a complex and diverse microbial population together breakdown and ferment the feed ingested by the host (Dehority, 2003). Methane (CH_4) and CO_2 are natural by-products of microbial fermentation of carbohydrates and, to a lesser extent, amino acids (AA) in the rumen and the hindgut of farm animals. Methane is produced in strictly anaerobic conditions by highly-specialized methanogenic archaea. Also, a large portion of the dietary protein and non-protein N compounds entering the rumen are degraded by ruminal microorganisms to peptides, aa and eventually to ammonia (NH_3) (Hristov and Jouany 2005). These compounds are used by rumen bacteria to synthesize protein. Ammonia is also absorbed into the blood stream, through the rumen wall or other sections of the gastrointestinal tract (Reynolds and Kristensen 2008) where it is converted to urea in the liver and excess is eliminated in urine, which is the main source of (NH_3) volatilized from cattle manure (Bussink and Oenema 1998).

Diet composition and intake are main factors affecting CH_4 production by ruminants. Ruminant fed forages rich in structural carbohydrates produce more CH_4 than those fed mixed diets containing higher levels of non-structural carbohydrates per unit of fermented material in the rumen (Sauvant and Giger-Reverdin, 2009). This is explained by the different metabolic routes used to ferment the different carbohydrates which result in different VFA profiles that yield more or less metabolic H_2 as the main substrate to produce CH_4 (Hristov et al., 2013). There is a clear relationship between feed organic matter digestibility, concentrate feed or starch intake, and the pattern of ruminal fermentation and CH_4 production. Also, in the last decade a vast amount of research has been published on the composition and metabolic characteristics of the rumen methanogenic archaea community with the objective of developing specific inhibitors (Morgavi et al., 2010).

With regards to NH_3 emissions, protein overfeeding to either the microbes or the animal will result in catabolism of the protein or amino acids, conversion of the excess N to urea, and excretion of urea in urine. Thus, from an environmental point of view, it is important to match dietary protein supplies as closely as possible to microbial and animal needs.

Regardless the specific target, the different mitigation options can be grouped into different 'levels of maturity' (GRA, 2014), indicating the readiness of the measure for implementation based on experiences in diverse settings (Table 1). Those levels can be outlined as:

- **Best practice:** measure has been successfully implemented in diverse contexts, next step is scaling up.
- **Pilot:** pilot project has been carried out, next step is commercial development
- **Proof of concept:** the measure has been demonstrated in an experimental setting, next step is a pilot.
- **Discovery:** exploring promising concepts for future proof of concept.

Table 1. Main feeding strategies to reduce CH₄ and NH₃ emissions

Mitigation strategy	Readiness	Main constraints for implementation
Forage quality	Best practice	Farmers awareness and appropriate training (extension service) or social environment Reluctant to change from traditional practices Commercial availability of appropriate genetic varieties for a given environment
Dietary ingredients	Best practice	Economic constraints (e.g. lipids)
Precision feeding	Best practice (intensive)	Economic costs of technology (animal id, feed supply)
Grass management	Best practice, Pilot (still knowledge gaps on some novel grass, mob grazing)	Dependency on weather conditions, knowledge gaps, Farmers awareness and appropriate training (extension service) or social environment Reluctant to change from traditional practices
Additives, plant compounds		
Improving rumen function (essential oils, tannins)	Between Best practice and pilot	Consistency in effectiveness, lack of knowledge on mode of action (diet depending), lack of clarity in the market
Specific Methane inhibitors (3nop, nitrate)	Pilot	Safety, toxicology, commercial availability
Protected aa	Best practice	Cost, applicable to high-producing herds or individual animals at particular periods

Strategies to reduce emissions

a) Forage quality

An important feed characteristic that can impact enteric CH₄ production is forage quality, specifically its digestibility. As noted by Blaxter and Clapperton (1965), increased intake of poor-quality, less digestible feeds has little effect on CH₄ production when expressed on a dry matter intake basis. For feeds with higher digestibility, however, increased intake results in a depression in the amount of CH₄ produced per unit of feed consumed. Moreover, it decreases CH₄ produced per unit of product (emission intensity) by diluting maintenance energy.

Forages are the feed ingredients with the largest variability in composition and have the largest impact on diet digestibility. Factors, such as plant species, variety, maturity at harvest and preservation can all affect forage quality and digestibility. In general terms, as the plant matures, the content in structural carbohydrates increases and that of more fermentable carbohydrates declines. Harvesting forages at the right time, depending on the type of forage, is important to maximize the amount and digestibility of nutrients supply by forages (Hristov et al., 2013). Also, the different processes used to conserve forages (hay, silage...) may negatively influence the nutritional value if not done properly. In the last decade a strong effort is now in place to develop forage varieties rich in desirable nutrients (lipids, water soluble carbohydrates...) that have shown promising mitigation effects as discussed in section d.

The CH₄ database compiled by Hristov et al. (2013) contained numerous references on effects of forage quality; pasture management, and processing on CH₄ production in various ruminant species. In general, CH₄ reductions are correlated with greater nutrient quality and digestibility, which are 2 attributes for which forage type and maturity might be indicators. Increasing quality or digestibility of forages will increase production efficiency and this will likely result in decreased CH₄. Keady et al. (2012) provided a comprehensive review of the effects of silage quality on animal performance in various production systems in Ireland. These authors concluded that a 10

g/kg increase in digestible organic matter concentration of grass silage DM could increase 1) daily milk yield of lactating dairy cows by 0.37 kg, 2) daily carcass gain of beef cattle by 28 g/head, 3) daily carcass gain of finishing lambs by 10 g/head, 4) lamb birth weight by 0.06 kg, and 5) ewe BW post-lambing by 1.45 kg. They also pointed to the critical effect of maturity on grass silage digestibility; each 1week delay in grass harvest reduced digestibility by 3 to 3.5 percentage points.

b) Dietary ingredients

Concentrate feeds and starch generally provide more digestible nutrients than roughages, which increase the digestibility of feed and generally lift animal productivity.

Starch is a possibility in some situations but can not be generalized (i.e. low input systems with slight supplementation with starch). The suitability of this approach for GHG mitigation depends on the access to and availability of feed and potential competition with direct human consumption.

By-product feeds with high oil contents, such as distiller grains and meals from the biodiesel industry, can be cost-effective lipid sources. There is a large body of evidence that lipids suppress CH₄ production. The effects of lipids on rumen archaea are not isolated from their overall suppressive effect on bacteria and protozoa (Hristov et al., 2013). Meta-analyses by Moate et al. (2011) and Grainger and Beauchemin (2011) documented a consistent decrease in CH₄ production with fat supplementation. Moate et al. (2011) reported the following relationship between dietary fat and CH₄ production per unit of DMI: $CH_4 \text{ (g/kg DM)} = 24.51 (\pm 1.48) - 0.0788 (\pm 0.0157) \times \text{fat (g/kg DM)}$. Grainger and Beauchemin (2011) analysed 27 studies and concluded that, within a practical feeding rate of less than 8% fat in the diet, a 10 g/kg increase in dietary fat would decrease CH₄ yield by 1 g/kg DMI in cattle. Although supplementing animal diets with edible lipids for the sole purpose of reducing CH₄ emissions is debatable, high-oil by-products from the biofuel industries [dry (DDG) or wet (WDG) distillers grains alone or with solubles (DDGS and WDGS, respectively) and mechanically extracted oilseed meals] can naturally serve as a CH₄ mitigating feed, if included in the diet to decrease feed cost (Hales et al., 2013).

c) Precision feeding

Two main aspects of ruminant nutrition can be related directly to NH₃ emissions from cattle manure: (1) inefficient utilization of feed N in the rumen; (2) inaccurate prediction of the animal degradable and undegradable protein requirements, leading to overfeeding of dietary N. A large portion of the dietary proteins and non-protein compounds entering the rumen are degraded by the ruminal microorganisms to peptides, amino acids, and eventually to NH₃. Available research data indicate that diets fed to animals have profound effects on NH₃ emissions from manure. Overfeeding of rumen degradable protein or metabolizable protein will result in excessive urinary N excretion. Feeding a diet imbalanced in aa supply can also result in poor feed N use efficiency because one or more amino acids can limit protein synthesis and thus the productive use of the other amino acids, resulting in increased catabolism of all amino acids. Finally, insufficient diet fermentability can limit N capture in microbial protein in the rumen, and insufficient energy supply to the animal can limit rates of protein synthesis, both of which result in poor feed N efficiency, excessive urinary N output and, consequently, increased NH₃ emissions from manure. Urinary N losses by dairy cows decrease linearly with decreasing dietary CP levels. These reductions can sometimes be achieved with minimal or no effects on yield or composition of milk and milk protein. More information on precision feeding is included in the Minipaper by Barzanas et al.

d) Grass management

Grasslands are an important source of low-cost and high-quality feed for ruminants in Europe. It is estimated that roughly half of the total dry matter intake by livestock at the global level comes from grass and other roughages, albeit with strong regional variations (GRA, 2014). Grassland soils also store large quantities of carbon and in many regions have the potential to sequester more carbon, while providing a range of other ecosystem services related to habitat and water quality. Improving management practices and breeding/adopting new species and cultivars can improve the quantity and quality of feed to animals and also, in some regions and systems, enhance soil carbon storage. However, the potential for carbon sequestration and techniques for achieving it are country/region specific, and differ across soil types, management practices and climate.

Developing grass varieties with specific traits aimed at improving feed efficiency or directly reducing emissions may be of significant importance for predominantly pasture-based ruminant production systems. The focus on

development and subsequent uptake of the so-called 'high sugar' grasses in the UK is one example. These have been shown to improve N utilisation by ruminants (Moorby et al., 2006), which would result in less nitrogen excretion and therefore less subsequent N₂O and ammonia emissions. They have also been shown in one UK trial to reduce enteric CH₄ emissions from grazing lambs by 20% (Defra, 2010), with the reduction hypothesised to be due to a combination of altered carbohydrate metabolism in the rumen towards propionate production (H-sink) and away from acetate formation (H-source) plus improved microbial growth through improved capture of N in the rumen, diverting surplus hydrogen away from CH₄ production and into microbial cells. However, a review by Parsons et al. (2011) was less conclusive on the effects of high sugar grasses and further research is needed to demonstrate both mechanism and effectiveness. Other targets for development include increasing the lipid content of grazed grasses, as lipids are known to suppress CH₄ production as discussed above (Section b) and to improve the quality/digestibility of the fibre content of grasses.

The inclusion of legumes in grassland for grazing or silage production has a direct benefit through the reduced requirement of fertiliser N input and therefore less direct N₂O emissions associated with fertiliser use. In addition, there is also evidence of an effect of legumes in reducing enteric methane emissions (Waghorn et al., 2002), although again this has not been shown consistently (e.g. Hammond et al., 2011). Including legumes in silage was reported to decrease methane by Dewhurst (2012) resulting from a lower fibre content and therefore higher passage rate through the rumen.

Potential pasture management practices to reduce emissions from grazing ruminants include shortening the duration of the grazing period (either a shorter period each day, or for a shorter season), removing grazing animals during conditions conducive to N₂O emissions, avoiding the development of 'hot-spots' for soil emission of N₂O or CH₄, and applying precision management techniques to the fertilisation and utilisation of pastures. The use of standoff pads in New Zealand grazing systems is increasing, where cattle are removed from the pasture for part of the day (particularly during wet soil conditions) and has been shown to be an effective measure for reducing N₂O emissions (Luo et al., 2008). However, there is a risk of increased NH₃ emissions from the management of the collected effluent, and these trade-offs must be considered in the context of system changes. Soil N₂O and CH₄ emissions from 'hot spots' which develop through cattle poaching and disproportionately high excretal returns, for example around water troughs, gateways and tracks, can represent a substantial part of the entire GHG footprint of a farm (Matthews et al., 2009). Grazing management practices to avoid such 'hot spots' might include regular movement of cattle between smaller paddocks (rotational grazing), regular movement of water troughs and temporary exclusion from poached areas. Precision pasture management techniques include the use of appropriate rates and timing of fertiliser N applications, planning of herbage production and quality in relation to livestock requirement through the season and managing livestock movement to ensure forage is grazed at optimum time in terms of quality and availability. These measures will improve production efficiency and reduce GHG emission per unit of production. Further discussion of mitigation through grassland management can be found in the Global Research Alliance report on Reducing greenhouse gas emissions from livestock (GRA, 2014).

Grazed pastures also offer potential for carbon sequestration, thus offsetting other GHG emissions, if managed well. In addition to parameters such as stocking density and level of inputs, the use of deep rooting grass/forage varieties to sequester carbon, the impacts and potential of mob grazing and the potential of silvo-pastoral (agroforestry) systems in this respect is needed to understand and realise their potential. These aspects have been considered to some extent in other Focus Groups (Permanent Grassland, and Agroforestry).

e) Feed additives, plant compounds

Fundamental understanding of the microbiome and the relation between host animals, methanogens and other micro-organisms is essential to be able to modify the rumen in a way that is consistent with farming practices, economics, and food safety requirements. Some chemical compounds can have an inhibitory effect on methane-generating rumen micro-organisms. Laboratory experiments have shown methane reductions in vitro of up to 100%. Some compounds have also been demonstrated to be effective in animal trials, with some resulting in almost complete removal of methane emissions; however, these are not commercially viable due to animal health and food safety concerns or prohibitive costs. Research is focussed on examining natural or synthetic compounds

that meet the requirements of long-term efficacy (including possible adaptation of the rumen microbial community), no negative effects on productivity, and food and animal safety.

It has been suggested that rumen function will be disrupted if methane production is significantly decreased by directly inhibiting methanogenic archaea without the provision of alternative hydrogen sinks (McAllister and Newbold, 2008), which implies that methane production is unavoidable in ruminant production systems. However, recent work (Abecia et al., 2012; Mitsumori et al., 2012) suggest that methane production ruminants can be significantly decreased by inhibiting the metabolism of methanogenic archaea with little effect on rumen function and diet digestibility. Indeed, studies on the rumen transcriptome suggest that the methane-inhibited rumen adapts to high hydrogen levels by shifting fermentation to alternative H sinks and direct emissions of H₂ from the rumen.

Given that methane emissions can be significantly reduced without affecting production and health attention should focus on the practical means by which this might be achieved. The greatest progress has been in the areas of diet and dietary additives to mitigate against ruminal methane emissions (Gerber et al., 2013), with decreases in excess of 60 % reported in cattle fed specific dietary additives (Haisan et al., 2014). Recent data (Hristov et al., 2015) suggest that, in many cases, additives enhance capacity to mitigate against ruminal CH₄ production. While perhaps technically possible to achieve considerable (above 50 %) reduction in methane emissions through the use of specific inhibitors, a number of practical issues need to be considered:

1. Nutrition: the combination of multiple additives/supplements, while potentially possible under experimental conditions, may prove impractical due to difficulties in formulation, including the inevitable dilution of nutritional value as additives account for an increasing share of the diet. Clearly, there is a need for increased research into additives that are effective at low levels of dietary inclusion.
2. Delivery: dietary additives may be applicable to housed ruminants but are far less applicable to extensively raised animals. Significant effort needs to be dedicated to delivery systems for extensively raised animals.
3. Developing a convincing economic model: taken as a whole, current research suggests that measurable production responses to methane mitigation are unlikely to occur. Thus, alternative methods to incentivize the use of what are likely to be expensive additives to decrease ruminal CH₄ production need to be developed.

A good example of compounds with potential is tannins which are both active as methane inhibitors and as modulators of NH₃ emissions from excreta. Condensed tannins (CT) are a broad class of polyphenolic secondary plant compounds that can be extracted from a wide variety of plants. Tannin concentration is likely an evolved plant defence against herbivores, as these compounds reduce protein metabolism. Tannin interaction with proteins, metal ions, and amino acids in ruminants can depress activity by methanogenic microbes in the rumen and thus decrease CH₄ emissions (Woodward et al. 2001). This indirect effect on CH₄ emissions is mainly due to the CT, which are more effective in the reduction in fibre digestion. On the other hand, hydrolysable tannins act more through inhibition of the growth and/or activity of methanogens and/or hydrogen-producing microbes, causing a direct effect on CH₄ emissions (Goel and Makkar, 2012). While individual studies on this topic are equivocal, a recent meta-analysis suggests that enteric CH₄ can be measurably depressed with the addition of CT at levels above 1 % feed dry matter intake (Jayanegara et al. 2012). Furthermore, most studies show that tannin additions up to 2 % do not impact cow milk production (Jayanegara et al. 2012). Also, previous work has demonstrated that NH₃ emissions are significantly less from manure excreted by cows fed 0.45 and 1.8 % CT when compared to cows fed no tannin (Aguerre et al. 2011;).

Rumen protected aa

Animals do not actually have a requirement for protein. Instead, they require the specific AA that are the building blocks that make up proteins (NRC, 2001). In most situations, by selecting proper protein sources and judiciously using rumen protected AA, it should be theoretically possible to balance the amino acid needs of the cow while reducing crude protein intake. Broderick et al (2008) published a study that demonstrated that a ration with 16.1% CP and added RP-Met resulted in the same amount of milk as a 17.3% CP ration without RP-Met, and both rations resulted in higher milk production than an 18.3% ration. There are current studies underway to further refine this relationship. This nutritional strategy is normally used only for high yield animals.

Farmers adoption

The farming sector needs to be more aware of the link between lowered emissions and increased efficiency. However, this not always results in economic benefits. It is clear that other encouragement policies should be implemented (i.e. subsidies, low interest loans.....)

Proposal for potential operational groups

- On farm application of feeding strategies aimed to mitigate methane emissions.
- Reliable decision tools for improving the forage quality at farm level.
- Efficient use of underutilized agro-industrial by-products in different regions of Europe.
- Development of on-farm or locally sourced protein sources (short distribution channels) and decision tools for matching protein supply to animal requirements in the ration.

Proposals for (research) needs from practice

- Improve means to deliver feed additives to reduce emissions particularly under grazing, low input farming conditions
- Identification of proxies for feed efficiency
- Identification and validation of non-invasive proxies of methane production for high throughput monitoring and breeding and management strategies.
- Improve N use efficiency (soil-plant-animal-food)

Project examples

- Integrating nutrition and genetics to develop lower methane livestock system and better use of resources. The project needs to consider the entire lifetime of the animals, integrating management, nutrition and genetics in a holistic manner.
- Towards a more efficient use of local feeds and agro-industrial by-products in livestock feeding.

References

- Abecia L, Toral P, Martín-García A, Martínez G, Tomkins N, Molina-Alcaide E, Newbold C & Yáñez-Ruiz DR. 2012. Effect of bromochloromethane on methane emission, rumen fermentation pattern, milk yield, and fatty acid profile in lactating dairy goats. *Journal of Dairy Science* 95: 2027-2036.
- Arndt. 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. *J. Dairy Sci.* 94:3081-3093.
- Blaxter KL, Clapperton JL. 1965. Prediction of the amount of methane produced by ruminants. *British Journal of Nutrition*, 19, 511-522
- Broderick, G. A. 1995. Desirable characteristics of forage legumes for improving protein utilization in ruminants. *J. Anim. Sci.* 73:2760-2773.
- Bussink, D. W. and Oenema, O. 1998. Ammonia volatilization from dairy farming systems in temperate areas: a review. *Nutr. Cycl. Agroecosyst.* 51: 19-33.
- Council for Agricultural Science and Technology (CAST). 2013. Animal Feed vs. Human Food: Challenges and Opportunities in Sustaining Animal Agriculture Toward 2050. Issue Paper 53. CAST, Ames, Iowa.
- Defra, 2010. Ruminant nutrition regimes to reduce methane and nitrogen emissions. Project AC0209 available at: <http://randd.defra.gov.uk/>
- Dehority, BA. 2003. Rumen microbiology. Nottingham University Press, 372 pp.
- Dewhurst, R.J., 2012. Milk production from silage: comparison of grass, legume and maize silages and their mixtures. In: K. Kuoppala, M. Rinne and A. Vanhatalo, eds., Proc. XVI Int. Silage Conf. MTT Agrifood Research Finland, University of Helsinki, Hameenlinna, Finland. P134-135.
- FAO. 2012. Biofuel co-products as livestock feed - Opportunities and challenges, edited by Harinder P.S. Makkar. Rome
- FAO (2013): Mitigation of greenhouse gas emissions in livestock production: A review of technical options for non-CO2 emissions. FAO Animal Production and Health Paper No. 177. Gerber, P.J. et al. (eds), Food and Agriculture Organisation of the United Nations (FAO), Rome.
- Gerber, P. J., A. N. Hristov, B. Henderson, H. Makkar, J. Oh, C. Lee, R. Meinen, F. Montes, T. Ott, J. Firkins, C. Dell AI Rotz, A. Adesogan, W. Z. Yang, J. Tricarico, E. Kebreab, G. Waghorn, J. Dijkstra, and S. Oosting. 2013. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock – A review. *Animal* 7(Suppl. 2):220-234.
- Goel, G. and H.P.S. Makkar. 2012. Methane mitigation from ruminants using tannins and saponins. *Trop Anim Health Prod.* 44:729-739.
- Grainger, C., and K. A. Beauchemin. 2011. Can enteric methane emissions from ruminants be lowered without lowering their production? *Anim. Feed Sci. Technol.* 166-167:308-320.
- GRA, 2014. Reducing greenhouse gas emissions from livestock: Best practice and emerging options. Global Research Alliance and SAI Platform. Available at (http://globalresearchalliance.org/wp-content/uploads/2014/12/LRG-SAI-Livestock-Mitigation_web2.pdf)
- Haisan, J., Y. Sun, K. Beauchemin, L. Guan, S. Duval, D. R. Barreda, and M. Oba. 2013. Effect of feeding 3-nitrooxypropanol on methane emissions and productivity of lactating dairy cows. *Adv. Anim. Biosci.* 4(2):260.
- Hales, K. E., N. A. Cole, and J. C. MacDonald. 2013. Effects of increasing concentrations of wet distillers grains with solubles in steam-flaked corn-based diets on energy metabolism, carbon-nitrogen balance, and methane emissions of cattle. *J. Anim. Sci.* 91:819-828.
- Hammond, K.J., Hoskin, S.O., Burke, J.L., Waghorn, G.C., Koolaard, J.P., Muetzel, S., 2011. Effects of feeding fresh white clover (*Trifolium repens*) or perennial ryegrass (*Lolium perenne*) on enteric methane emissions from sheep. *Anim. Feed Sci. Technol.* 166-167, 398-404.
- Hristov A. N., Jouany J. P. 2005. "Factors affecting the efficiency of nitrogen utilization in the rumen," in Nitrogen and Phosphorus Nutrition of Cattle and Environment, eds Hristov A. N., Pfeffer E., editors. (Wallingford: CAB International;), 177-166.
- Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B., Tricarico, J.M., 2013. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *J. Anim. Sci.* 91, 5045-5069.

- Hristov et al. 2015. An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. *PNAS*, 112 | no. 34 | 10663–10668.
- Intergovernmental Panel on Climate Change (IPCC). 2006. Chapter 10. Emissions from livestock and manure management. In: *Guidelines for national greenhouse inventories*. Vol. 4. Agriculture, forestry and other land use. IPCC, Geneva, Switzerland. p. 10.1–10.87.
- Jayanegara, A., F. Leiber, and M. Kreuzer. 2012. Meta-analysis of the relationship between dietary tannin level and methane formation in ruminants from in vivo and in vitro experiments. *J. Anim. Physiol. Anim. Nutr. (Berl.)* 96:365–375.
- Keady, T. W. J., C. M. Marley, and N. D. Scollan. 2012. Grass and alternative forage silages for beef cattle and sheep: Effects on animal performance. In: K. Kuoppala, M. Rinne, and A. Vanhatalo, editors, *Proc. XVI Int. Silage Conf.* Hameenlinna, Finland. MTT Agrifood Research Finland, University of Helsinki. p. 152–165.
- Luo, J., Ledgard, S.F., Lindsey, S.B., 2008. A test of a winter farm management option for mitigating nitrous oxide emissions from a dairy farm. *Soil Use Manage.* 24, 121-130.
- Matthews, R.A., Chadwick, D.R., Retter, A.L., Blackwell, M.S.A., Yamulki, S., 2010. Nitrous oxide emissions from small-scale farmland features of UK livestock farming systems. *Agric. Ecosyst. Environ.* 136, 192-198.
- McAllister T & Newbold CJ (2008) Redirecting rumen fermentation to reduce methanogenesis. *Australian Journal of Experimental Agriculture* 48: 7-13.
- Mitsumori M, Shinkai T, Takenaka A, Enishi O, Higuchi K, Kobayashi Y, Nonaka I, Asanuma N, Denman SE & McSweeney CS. 2012. Responses in digestion, rumen fermentation and microbial populations to inhibition of methane formation by a halogenated methane analogue. *British Journal of Nutrition* 108: 482-491.
- Moate, P. J., S. R. O. Williams, C. Grainger, M. C. Hannah, E. N. Pon-nampalam, and R. J. Eckard. 2011. Influence of cold-pressed canola, brewers grains and hominy meal as dietary supplements suitable for reducing enteric methane emissions from lactating dairy cows. *Anim. Feed Sci. Technol.* 166–167:254–264.
- Moorby, J.M., Evans, R.T., Scollan, N.D., Macraet, J.C., Theodorou, M.K., 2006. Increased concentration of water-soluble carbohydrate in perennial ryegrass (*Lolium perenne* L.). Evaluation in dairy cows in early lactation. *Grass Forage Sci.* 61, 52-59.
- Morgavi D, Forano E, Martin C & Newbold CJ (2010) Microbial ecosystem and methanogenesis in ruminants. *Animal* 4: 1024-1036.
- NRC. 2001. *Nutrient requirements of dairy cattle*. 7th rev. ed. Natl. Acad. Press, Washington, DC.
- Parsons, A.J., Rowarth, J.S., Rasmussen, S., 2011. High-sugar grasses. *CAB Rev.* 6, 1-12.
- Reynolds C K, and Kristensen NB. 2008. Nitrogen recycling through the gut and the nitrogen economy of ruminants: An asynchronous symbiosis. *Journal Animal Science*. 86 No. 14_suppl, p. E293-E305.
- Sauvant, D., and S. Giger-Reverdin. 2009. Modélisation des interactions digestives et de la production de méthane chez les ruminants. *INRA Prod. Anim.* 22:375–384.
- Waghorn, G.C., Tavendale, M.H., Woodfield, D.R., 2002. Methanogenesis from forages fed to sheep. *Proc. N. Z. Grassland Assoc.* 64, 167-171.
- Woodward, S. L., G. C. Waghorn, M. J. Ulyatt, and K. R. Lassey. 2001. Early indications that feeding Lotus will reduce methane emissions from ruminants. *Proc. N.Z. Soc. Anim. Prod.* 61:23–26.