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Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review

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Although livestock production accounts for a sizeable share of global greenhouse gas emissions, numerous technical options have been identified to mitigate these emissions. In this review, a subset of these options, which have proven to be effective, are discussed. These include measures to reduce CH_4 emissions from enteric fermentation by ruminants, the largest single emission source from the global livestock sector, and for reducing CH_4 and N_2O emissions from manure. A unique feature of this review is the high level of attention given to interactions between mitigation options and productivity. Among the feed supplement options for lowering enteric emissions, dietary lipids, nitrates and ionophores are identified as the most effective. Forage quality, feed processing and precision feeding have the best prospects among the various available feed and feed management measures. With regard to manure, dietary measures that reduce the amount of N excreted (e.g. better matching of dietary protein to animal needs), shift N excretion from urine to faeces (e.g. tannin inclusion at low levels) and reduce the amount of fermentable organic matter excreted are recommended. Among the many 'end-of-pipe' measures available for manure management, approaches that capture and/or process CH_4 emissions during storage (e.g. anaerobic digestion, biofiltration, composting), as well as subsurface injection of manure, are among the most encouraging options flagged in this section of the review. The importance of a multiple gas perspective is critical when assessing mitigation potentials, because most of the options reviewed show strong interactions among sources of greenhouse gas (GHG) emissions. The paper reviews current knowledge on potential pollution swapping, whereby the reduction of one GHG or emission source leads to unintended increases in another.

Keywords: greenhouse gases, climate change, animal production, animal feeding, manure management

Implications

The paper reports on technical options for the mitigation of livestock sector's contribution to climate change. On the basis of a comprehensive review of *in vivo* studies, it provides the researcher and the livestock sector stakeholder with concise information on exiting mitigation practices, their effectiveness and interactions. Uncertainties and areas for further research are also highlighted. It is hoped that the paper will contribute to the identification of lower greenhouse gas -emission pathways for livestock production.

Introduction

In view of livestock's sizeable contribution to global warming, this review assesses the veracity, efficacy and feasibility of the many mitigation options that have been put forward by practitioners and researchers over the past few decades. This review spans the breadth of the literature on mitigation, drawing primarily on a recent comprehensive review of mitigation measures for livestock by Hristov *et al.* (2013), which incorporates information from over 900 references. This review also benefitted from an expert consultation, which assembled leading global scientists to peer-review and improve the review by Hristov *et al.* (2013). Much of the discussion on

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interactions between mitigation practices and greenhouse gases (GHGs) in this paper is derived from the workshop.

Livestock production plays a crucial role in food security, rural livelihoods and development at large (Herrero *et al.*, 2013). It also accounts for a substantial share of global anthropogenic GHG. If all emissions along the livestock supply chain are considered, this contribution amounts to 7.1 Gt CO_2-eq, for the 2005 reference period (FAO, 2013a and 2013b). When considering only the direct CH_4 and N_2O emissions from enteric fermentation and manure (including its application), livestock are estimated to contribute 5.4 Gt CO_2-eq to global emissions (FAO, 2013a and 2013b).

Large differences in emission intensities and/or quantities are observed between species, regions and production systems. When considering total supply chain emissions, cattle (beef and dairy) production generates 4.6 Gt, the largest share of global livestock emissions by some margin. This figure drops to a still significant 3.3 Gt when only the direct CH_4 and N_2O emissions from enteric fermentation and manure are considered (FAO, 2013b). This massive contribution stems from cattle's dominant global share of live animal biomass and, like all ruminant animals, from their fermentative digestive system.

Other livestock species have much lower and similar levels of emissions, even when considering the full lifecycle of emissions: pigs (0.7 Gt CO_2-eq), poultry (0.7 Gt CO_2-eq), buffalo (0.6 Gt CO_2-eq) and small ruminants (0.5 Gt CO_2-eq) (FAO, 2013a and 2013b).

Of the 3.3 Gt of direct cattle GHG emissions, CH_4 from enteric fermentation is the largest source, accounting for a 71% share. Manure N_2O, particularly from deposition on pasture, accounts for the next largest share (25%), whereas the remaining 4% is from manure CH_4 (FAO, 2013b).

Direct emissions typically account for 15% and 35% in poultry and pig production, respectively. Emissions related to manure storage and processing are important for pig supply chains with 27% of emissions (FAO, 2013a).

In addition to direct emissions, livestock supply chains release GHG through animal feed production and post-harvest activities. Feed production is the main source of indirect emissions and is particularly important for the monogastric sector. Emissions (primarily N_2O) from feed production are almost equal in size to direct emissions. They represent 36% of cattle supply chain emissions, 60% of pork supply chains emissions and 75% for chicken and egg supply chains. A lifecycle framework can be used to account for these feed emissions, as well as those from off-farm emission sources (e.g. from processing, transport and land-use change) (FAO, 2013a and 2013b).

Emissions related to land-use change for pasture or feed crop expansion are insignificant. They represent almost 15% of emissions for beef, 13% for pigs and 18% for chicken. Broiler rations include a higher share of soy sourced from areas where land-use conversion is taking place, whereas land-use change emissions are of little importance for the dairy sector. Energy consumption along the supply chain contribute a significant share of emissions, especially in monogastric production where they can represent up to 40% of emissions in chicken production (FAO, 2013a).

The emission intensity (Ei) of a commodity, measured as the quantity of GHG emissions generated per unit of output, is a useful metric for several reasons. It allows for meaningful comparison of emissions especially within, but also between, commodities. It is also very closely linked to the productivity of the system, measured in terms of output per animal, or on a whole herd basis. Moreover, as productivity improvements can increase profits at the same time as lowering Ei, they may also present opportunities to profitably invest in mitigation. The Ei metric can also accommodate emission reductions (or emissions stabilization) alongside expanding output, which is important, given that livestock commodity production is projected to grow at a steady pace until at least the middle of this century. Mitigation measures that improve productivity also have the best prospects for minimizing the trade-offs between mitigation, food security and producer welfare. At the same time, profitable productivity improvements will, in many cases, encourage the sector to expand; therefore, from a policy perspective they are necessary options, which can only be sufficient for mitigation if coupled with policies to restrict the sector's total quantity of emissions.

This review focuses on mitigation options for direct emissions: enteric CH_4 mitigation practices for ruminant animals (only *in vivo* studies were considered in the original review by Hristov *et al.*, 2013) and manure mitigation practices for both ruminant and monogastric species. Mitigation options that reduce Ei only by increasing herd productivity (e.g. animal husbandry, genetics and health management) while keeping herd GHG output constant (or increasing it proportionally less than productivity) are not included in this review, despite their great relevance among low-intensity ruminant systems (Gerber *et al.*, 2011; FAO, 2013a and 2013b).

In the following section, mitigation options for reducing enteric CH_4 production are reviewed. These options fall into two broad categories of feed supplements and feeds/feeding management. Following this, mitigation options for manure management are reviewed. These include dietary management options, but the focus is mainly on a range of 'end-of-pipe' options for the storage, handling and application phases of manure management.

After this, the role of interactions between mitigation options, productivity and emission sources is explored for both ruminant and monogastric animals. Particular attention is given to the risks of pollution swapping, as well as other possible unintended impacts of mitigation.

Mitigation options for enteric methane emissions

Methane and CO_2 are the major by-products of microbial fermentation of carbohydrates in the rumen and both are GHGs. Methane is produced in the anaerobic conditions of the rumen by archaea. In ruminants, the vast majority of enteric CH_4 production occurs in the reticulo-rumen. Rectal emissions account for a marginal share of emissions (Murray *et al.*, 1976; Muñoz *et al.,* 2012). A number of approaches, evaluated for mitigation of enteric CH_4, are presented in Table 1.

Table 1 *Technical options for the mitigation of enteric methane emissions and their interactions with other categories of emissions*

Mitigation option for enteric methane emissions				Interactions and overall effectiveness		
Mitigation technique	Effectiveness[1]	Domain of relevance	Estimated emissions in domain of relevance (Mt CO_2-eq)[2]	Interactions with other categories of emissions	Overall effectiveness, including interactions	Ei reduction through productivity enhancement
Feed supplements						
Dietary lipids	Medium	Confined and mixed ruminant systems of all regions Dairy cattle in grazing systems of North America, Europe, East Asia, Latin America and Oceania	2319	Can reduce feed digestibility and this increases CH_4 from stored manure. If source is from oil seeds (e.g. cotton), then it can increase N content of feed, and thus of excreata. Not recommended if base feed has high protein content. Oil supplementation should not exceed 6% and is not recommended if diet is of low quality (digestibility $< 50\%$).	Yes	Yes, in the case of baseline diet with low energy content
Nitrate (electron receptor)	High	All ruminant systems, in all regions	2710	Potential toxicity. Potential increased N_2O emissions from urine and manure, including deposition and application	Variable	None
Ionophores	Low	Confined beef production, outside EU27	124	Potential increase in N_2O emissions from urine and manure, including through manure deposition and application	Yes	Yes
Tannins	Low	All ruminant systems, in all regions	2710	Decrease in urine-N and potential lower emission of N_2O	Yes	None or Ei increase
Feeds and feeding management						
Concentrate inclusion in diet	Low to medium (if inclusion levels $>$ 35%)	All ruminant confined and mixed systems, in all regions	2249	Fibre digestibility of the ration can decrease if the ration contains more than 40% of starchy concentrates. Can lead to higher volatile solids excretion in manure and to higher CH_4 emissions during storage. Higher-feed digestibility leads to lower replenishment of soil C through manure deposition and application.	Yes, if $>$35 to 40%)	Yes, even at low levels of inclusion
Improving forage quality	Low to medium	All ruminant systems, in all regions	2710	If CP content of diet exceeds protein requirement of animal, N_2O emissions may increase Increased digestibility can reduce CH_4 from stored manure. Can increase overall intake and thus increase enteric CH_4 emissions in grazing systems. Legume introduction in pasture can reduce emissions related to fertilizer use. Effect on soil C is variable, depending on agronomic practices and plant physiology.	Variable	Yes

Table 1 *Continued*

Mitigation option for enteric methane emissions				Interactions and overall effectiveness		
Mitigation technique	Effectiveness[1]	Domain of relevance	Estimated emissions in domain of relevance (Mt CO_2-eq)[2]	Interactions with other categories of emissions	Overall effectiveness, including interactions	Ei reduction through productivity enhancement
Grazing management	Low to medium	All ruminant grazing and mixed systems, in all regions	2434	Optimize productivity per ha, by maximizing digestible dry matter intake Stocking rates may not be optimal for soil C. If CP content of diet exceeds protein requirement of animal, N_2O emissions may increase	Variable	Yes
Feed processing (grains)	Low	All ruminant confined and mixed systems, in all regions	2249	May have mitigation effect on N_2O emissions from manure application, and on CH_4 emissions from stored manure	Yes	Yes
Alkaline treatment	Low	All ruminant in mixed systems, in all regions	2132	Can increase NH_3 emissions if urea is used. Can increase in feed intake	No, emissions can increase	Yes
		Confined ruminant systems of Asia, Latin America, Sub Saharan Africa and Middle East/North Africa.				
Precision feeding	Low	All ruminant confined systems, in all regions	276	Contributes to the reduction of manure CH_4 and N_2O emissions	Yes	Yes
Strategic supplementation	Medium	All ruminant grazing systems, in all regions	2220	Can increase feed intake (leading to higher absolute enteric CH_4) Increases N and volatile solids in manure, thus manure CH_4 and N_2O emissions	No, emissions can increase	Yes, can be substantial
		Mixed systems in Eastern Europe, Asia, Latin America, Sub saharan Africa and Middle East/North Africa.				

[1] Low = ⩽ 10% mitigating effect; medium = 10 to 30% mitigating effect; high = ⩾ 30% mitigating effect. Mitigating effects refer to percent change over a 'standard practice', that is, study control that was used for comparison and are based on combination of study data and judgement by the authors of this document. For a detailed discussion, see Hristov *et al.* (2013).

[2] Estimates based on FAO (2013a and 2013b).

Mitigation options assessed but not recommended by Hristov *et al.* (2013), such as rumen archaea inhibitors (e.g. bromochloromethane), exogenous enzymes, rumen defaunation and yeast-based probiotics are not included in this review.

Vaccines against archaea have been successful *in vitro* (Wedlock *et al.*, 2010) and are a very promising option that could be applied to all ruminants, even in grazing situations with little human contact. As there are currently no vaccines that are ready for practical application (Clark *et al.*, 2004; Wright *et al.*, 2004) and they are also discussed in another review at this meeting (Wedlock *et al.*, 2013), they are excluded from this review.

Feed supplements

Dietary lipids. On the basis of several studies (Eugene *et al.*, 2008; Grainger and Beauchemin 2011; Rabiee *et al.*, 2012), Hristov *et al.* (2013) conclude that lipids are effective in reducing enteric CH_4 emission, but the feasibility of this mitigation practice depends on affordability of oil products and potential negative effects on animal productivity, for example, reduction in fibre digestibility. Although Eugène *et al.* (2011) reported that the combination of CH_4 reductions and reduced dry matter intake (DMI) resulted in no difference in CH_4 per unit of DMI, Rabiee *et al.* (2012) reported consistent reductions in CH_4 production per unit of DMI, or Ei for dairy cows. Grainger and Beauchemin (2011) concluded that with up to 8% fat in the diet, a 10 g/kg increase in dietary fat would decrease CH_4 yield by 1 g/kg DMI in cattle and 2.6 g/kg in sheep. However, the effect of these treatments on animal production over a longer time period was not reported. The important question of persistence of the effect of lipids on CH_4 production has not been adequately addressed (Woodward *et al.*, 2006). Some studies do report long-term effects of dietary lipids, but data are inconsistent (Holter *et al.*, 1992; Grainger *et al.*, 2008 and 2010b; Grainger and Beauchemin, 2011).

Electron receptors. Recent research on sheep (Sar *et al.*, 2004; Nolan *et al.*, 2010; van Zijderveld *et al.*, 2010) and cattle (van Zijderveld *et al.*, 2011a and 2011b; Hulshof *et al.*, 2012) has shown promising results with nitrates decreasing enteric CH_4 production by up to 50%. Nitrates may be particularly attractive in developing countries where forages contain negligible levels of nitrate and insufficient CP for maintaining animal production. When nitrates are used, it is critical that the animals are properly adapted to avoid nitrite toxicity (Hristov *et al.*, 2013). Adding sulfate to the diet of sheep reduced CH_4 production, but their potential effects on animal health are unclear. Other electron acceptors such as fumaric and malic acids may reduce CH_4 production when applied in large quantities, but most results indicate no mitigating effect and their costs are likely to be prohibitive (Hristov *et al.*, 2013).

Ionophores. A meta-analysis of 22 controlled studies concluded that monensin had stronger anti-methanogenic effect in beef steers than dairy cows, but the effects in dairy cows can potentially be improved by dietary modifications and increasing monensin dose (E. Kebreab, 2012, University of California—Davis, USA, personal communication). Other meta-analyses have shown monensin to improve feed efficiency in beef cattle in feedlots (by 7.5%; Goodrich *et al.*, 1984) and on pasture (by 15%; Potter *et al.*, 1986), and for dairy cows (by 2.5%; Duffield *et al.*, 2008), which can lower enteric CH_4 Ei. However, ionophores are banned in the European Union, and therefore not applicable everywhere. On the basis of the available information, it is surmised that ionophores, through their effect on feed efficiency, would likely have a moderate CH_4-mitigating effect in ruminants fed high-grain or grain-forage diets. This effect is less consistent in ruminants fed pasture (Hristov *et al.*, 2013).

Tannins and saponins. Tannins as feed supplements or as tanniferous plants have often, but not always (Beauchemin *et al.*, 2007a), shown potential for reducing enteric CH_4 emissions, in some cases by up to 20% (Sliwinski *et al.*, 2002; Zhou *et al.*, 2011a; Staerfl *et al.*, 2012).

However, the effects of tannins on animal digestion and productivity are variable between studies. Some of the variation may be explained by the type, concentration and protein-binding capacity of the tannins, the type of technique used to measure the tannin concentration and failure to distinguish between condensed and hydrolyzable tannins (Makkar, 2003). In an extensive review of the effect of saponins and tannins on CH_4 production in ruminants, mostly on the basis of *in vivo* studies, Goel and Makkar (2012) concluded that the risk of impaired rumen function and animal productivity is greater with tannins than with saponins.

Hydrolyzable and condensed tannins may thus offer an opportunity to reduce enteric CH_4 production, although intake and animal production may be compromised. Tea saponins seem to have shown some potential, but more and long-term studies are required before they could be recommended for use (Hristov *et al.*, 2013).

Feeds and feeding management

Feed intake. Feed intake is an important variable in predicting CH_4 emissions. Johnson and Johnson (1995) stated that CH_4 loss as a percentage of gross energy intake (Ym) decreases by 1.6% units per each level of intake above maintenance. For growing lambs on pasture, Hegarty *et al.* (2010) predicted both a linear increase in average daily gain (ADG) and an increase in CH_4 production, with increased DMI, with the rate of ADG being greater for feeds of greater digestibility. Further, as the amount of CH_4 released per unit of additional intake is greater for lower-digestibility feeds, the Ei of growth at any given DMI is less for high-digestibility feeds than for low-digestibility feeds. Moreover, small changes in energy intake result in small changes in CH_4 output, but in large changes in animal performance (Hegarty *et al.*, 2010).

Concentrate inclusion in the diet. Hristov *et al.* (2013) concluded that the inclusion of concentrate feeds in the diet of ruminants will likely decrease enteric CH_4, particularly when inclusion is above 35% to 40% of DMI (based on a meta-analysis by Sauvant and Giger-Reverdin, 2009). However, the effect will depend on inclusion level, type of grain and grain processing, fibre digestibility, rumen function and production responses. Although supplementation with small amounts of concentrate feeds will increase animal productivity and thus decrease GHG Ei, if the emissions from concentrate feed production are included, absolute GHG emissions may not always decrease (FAO, 2013b). Furthermore, concentrate inclusion may not be an economically feasible and socially acceptable mitigation option in many parts of the world (Hristov *et al.*, 2013).

Forage quality and management. Harvesting forage at an earlier stage of maturity increases its soluble carbohydrate content and reduces lignification of plant cell walls, thereby increasing its digestibility (Van Soest, 1994), and decreasing enteric CH_4 production per unit of digestible dry matter (Tyrrell *et al.*, 1992; Boadi and Wittenberg, 2002). However, effects of forage quality on methane production are often contradictory (Hart *et al.,* 2009).

High-sugar grasses (i.e. grasses with elevated concentrations of water-soluble carbohydrates) have been investigated as a tool for mitigating the environmental impact of livestock. These forages may have some mitigation effect on N losses, but the prospect for reducing enteric CH_4 emissions is uncertain (Parsons *et al.*, 2011). No effect of high-sugar grasses on CH_4 emissions in dairy cows was reported by Staerfl *et al.* (2012).

In a meta-analysis of data generated with grasses and legumes, Archimède *et al.* (2011) showed that C4 grasses produce greater amount of enteric CH_4 than C3 grasses, and recommended the use of legumes in warm climates as a mitigation option, as animals fed warm climate legumes produced 20% less CH_4 than animals fed C4 grasses. However, low persistence and a need for long establishment periods are important agronomic constraints for this option (Hristov *et al.*, 2013). Pasture management can also be an important CH_4-mitigation practice. DeRamus *et al.* (2003) demonstrated that management-intensive grazing offered a more efficient use of grazed forage crops and more efficient conversion of forage into meat and milk, which resulted in a 22% reduction of projected CH_4 annual emissions from beef cattle. A study from Canada (McCaughey *et al.*, 1999) reported lower enteric CH_4 losses in beef cattle grazing alfalfa grass pastures than in cows grazing grass-only pastures. Studies by Waghorn *et al.* (2002) showed sheep fed white clover, *Lotus pedunculatus*, and other legumes had much lower CH_4 yields compared with sheep fed ryegrass.

Feed processing. In ruminants, forage particle size reduction through mechanical processing or chewing is an important component of enhancing forage digestibility, providing greater microbial access to the substrate, reducing energy expenditures and increasing passage rate, feed intake and animal productivity (Hristov *et al.*, 2013). A recent study by Hales *et al.* (2012b) with steers compared dry-rolled *v.* steam-flaked corn and reported increased digestibility and about 17% less CH_4 emissions (per unit of DMI) with the latter treatment. Although processing of grain is likely to reduce enteric CH_4 production per unit of animal product, caution should be exercised so that this does not result in decreased fibre digestibility (Hristov *et al.*, 2013). In low-input production systems, more minimal approaches to grain processing will be more economically feasible.

Precision feeding. Precision feeding would likely have an indirect effect on enteric CH_4 emissions through maintaining a healthy rumen and maximizing microbial protein synthesis, which is important for maximizing feed efficiency and decreasing CH_4 Ei (Hristov *et al.*, 2013). Precision feeding requires specific feed resources, equipment and management discipline. For subsistence and extensive farmers, lack of data on the nutrient requirements of native animal breeds and on the quality feed resources will hamper precision feeding (Hristov *et al.*, 2013). Nevertheless, there are examples of the positive effects of proper diet formulation on animal productivity and enteric CH_4 mitigation in developing countries. In experiments with lactating cattle and buffalo in India, Garg *et al.* (2012) showed that balancing feed rations significantly improved milk yield by 2% to 14% and increased milk fat by 0.2% to 15%, and also improved feed-conversion efficiency, milk N efficiency and net daily income.

Mitigation options for manure management

Manure management includes the accumulation of manure in animal houses, its collection, storage, processing and application, as well as the direct deposition of manure on pasture. Throughout these management activities, CH_4, N_2O and NH_3 are emitted, with the latter not being a GHG but potentially leading to indirect N_2O emissions.

Most of the CH_4 emissions resulting from manure are produced under anaerobic conditions during storage, with very little coming from land application. Nitrous oxide is directly produced through microbial nitrification under aerobic conditions and partial denitrification under anaerobic conditions (USEPA, 2010). Nitrous oxide can also be produced indirectly when manure N is lost through volatilization as NH_3, nitric oxide and nitrogen dioxide (NOx), or run-off and leaching is nitrified and denitrified in soil following redeposition (USEPA, 2010).

A broad range of technical options to mitigate GHG emissions during manure management have been evaluated by Hristov *et al.* (2013). The recommended options are introduced below and summarized in Table 2.

Diet manipulation

Diet can have a profound effect on manure emissions, as it drives the volume and composition of manure. In particular, diet affects the amount, form and partition of N excretion between urine and faeces, and the amount of fermentable organic matter (OM) excreted (Hristov *et al.*, 2013).

Reducing dietary CP and ruminally degradable protein concentration can reduce NH_3 emissions from manure,

Table 2 *Technical options for the mitigation of manure methane and nitrous oxide emissions, and their interactions with other categories of emissions*

Mitigation option	Effectiveness and targeted gas[1]	Domain of relevance	Estimated manure CH_4emissions in domain of relevance (Mt CO_2-eq)[2]	Estimated manure N_2O emissions in domain of relevance (Mt CO_2-eq)[2,3]	Main interactions with other categories of emission	Overall mitigation effect, including interactions
Diet manipulation						
Balanced dietary protein	Medium (N_2O)	All animals in all systems, except for monogastrics in backyard systems and ruminants in grazing systems of Asia, SubSaharan Africa and NorthAfrica/Middle East	264	1222	Can increase overall intake and thus increase enteric CH_4 emissions in grazing and mixed systems	Yes
Tannins	Low (N_2O)	All ruminant systems in all regions	144	1237	Can lead to lower intake in high tannin browsers	None, emissions may increase
Housing system	High (CH_4 and N_2O)	All animals in all systems, except for grazing ruminants, all regions	275	335	None observed	Yes
Biofiltration	Low (CH_4)	All animals in confined systems in all regions	133	80	Strong decrease of NH_3 emissions, leading to reduced indirect N_2O emissions. N_2O emissions can take place at disposal/ maintenance of biofilter.	Variable
Manure storage						
Decreased storage time	High (CH_4 and N_2O)	All animals in all systems, except for grazing ruminants, all regions	275	335	May displace emissions at level of manure application. Shorter storage time means more frequent application, which has both, positive and negative effects depending on season.	Variable
Natural or induced crust	High (CH_4)	All animals in confined and mixed systems, except for monogastrics in backyard systems, all regions	232	290	May also reduce NH_3 emissions May increase N_2O emission May increase NH_3 emissions (thus increase in indirect N_2O emissions) during application	Yes if NH_4 is captured by plant, thus limiting N_2O emission at time of application
Sealed storage with flare	High (CH_4 and N_2O)	Ruminant in confined systems and monogastrics in intensive and intermediate systems, all regions	133	80	May increase N_2O emissions, including increase in indirect emissions from NH_3 losses	Variable
Forced aeration	Medium to high (CH_4)	Monogastrics in intensive and semi-intensive systems North America, Latin America, Europe, East and South East Asia, Oceania	102	44	High energy consumption can result in increase in CO_2 emissions	Yes
Manure acidification	Low (N_2O)	Ruminant in confined and mixed systems and monogastrics in intensive and semi-intensive systems. North America, Latin America, Europe, East and South East Asia, Oceania	165	145	Reduces indirect N_2O emissions from NH_3 losses but may cause increase in direct N_2O emissions.	Yes
Composting	High (CH_4)	All animals in all systems, except for grazing ruminants, all regions	275	335	Increases NH_3 and N_2O emissions May contribute to increase in soil C through stabilization of organic matter Mechanized systems can be energy intensive, resulting in increased CO_2 emissions	Yes

Table 2 *Continued*

Mitigation option	Effectiveness and targeted gas[1]	Domain of relevance	Estimated manure CH_4emissions in domain of relevance (Mt CO_2-eq)[2]	Estimated manure N_2O emissions in domain of relevance (Mt CO_2-eq)[23]	Main interactions with other categories of emission	Overall mitigation effect, including interactions
Anaerobic digestion	High (CH_4)	All animals in all systems, except for grazing ruminants, all regions	275	335	May increase NH_3 during storage and application of liquor Biogas generated can substitute fossil energy consumption.	Yes
Manure application						
Manure incorporation in soil	Low (N_2O)	Ruminant in confined and mixed systems and monogastrics in intensive and semi-intensive systems North America, Latin America, Europe, East and South East Asia, Oceania	not calculated (marginal)	256	Reduces indirect N_2O emissions from NH_3 losses but may cause increase in direct N_2O and CH_4 emissions. May reduce N-fertilizer consumption (and related emissions) through better use of manure N	Variable
Time of application	Low (CH_4) to High (N_2O)	All animals in all systems, except for grazing ruminants, all regions	not calculated (marginal)	435	May result in increase in NH_3 losses May reduce N-fertilizer consumption (and related emissions) through better use of manure N	Yes
Standoff pads (Kraals)	Medium to high (N_2O)	Ruminants in mixed and grazing systems, all regions	not calculated (marginal)	559	Can increase CH_4 if manure in areas of concentration is stored in anaerobic conditions May reduce N-fertilizer consumption (and related emissions) through better use of manure N	Variable
Nitrification inhibitor applied to pastures	High (N_2O)	Ruminants in mixed and grazing systems. North America, Latin America, Europe, East and South East Asia, Oceania	not calculated (marginal)	318	Can result in higher NH_3 emissions, depending on storage conditions and time prior to application Can increase pasture productivity and/or displace N fertilizer	Yes
Urease inhibitors applied at time of excretion/ urination	Medium (N_2O)	Ruminant in confined and mixed systems and monogastrics in intensive and intermediate systems, all regions	not calculated (marginal)	691	Reduces indirect N_2O emissions from NH_3 losses but may increase direct N_2O and CH_4 emissions	Unclear, emissions may increase

[1] Low = ⩽10% mitigating effect; medium = 10 to 30% mitigating effect; High= ⩾ 30% mitigatin g effect. Mitigating effects refer to percent change over a 'standard practice', that is, study control that was used for comparison and are based on combination of study data and judgement by the authors of this document. For a detailed discussion, see Hristov *et al.* (2013).

[2] Estimates based on FAO (2013a and 2013b).

[3] Includes emissions from manure application and deposition when addressed by the mitigation option.

through a marked reduction of urinary urea excretion, NH_3 concentration and potentially N_2O emissions from dairy manure (Külling *et al.*, 2001; Agle *et al.*, 2010a; Luo *et al.*, 2010; Lee *et al.*, 2012; Schils *et al.*, 2013).

However, feed intake depression with protein- and amino acid-deficient diets has been demonstrated with pigs and poultry (Henry, 1985; Picard *et al.*, 1993) and must be avoided to maintain production efficiency. Amino acid supplements can be combined with dietary protein reductions to maintain feed conversion efficiency and prevent production losses (Ball and Mohn, 2003; Mosnier *et al.*, 2011; Osada *et al.*, 2011). For example, Cromwell and Coffey (1993) reported a 17% to 23% decrease in N excretion when dietary protein was reduced by 2% units and the diet was supplemented with synthetic lysine.

Shifting N excretions from urine to faeces is expected to reduce N_2O emissions from manure application because of the lower concentration of available N in manure, depending on manure storage time and conditions (Hristov *et al.*, 2013). Tannin supplements and tanniferous forages can be used for this purpose and have been shown to reduce urinary N as proportion of total N losses by 9.3% (Carulla *et al.*, 2005) and 25% (Misselbrook *et al.*, 2005a). Tannin use can also decrease N-release rate from manure, and thus affect manure-N availability for plant growth (Hristov *et al.*, 2013).

Feed additives can also reduce CH_4 emissions from pig and poultry manure. For example, the addition of thymol to sow diets reduced CH_4 emissions from sow manure by up to 93% (Varel and Wells, 2007).

In general, feeding protein close to animal requirements, including varying protein concentration with stage of lactation, laying or growth, is recommended as an effective manure NH_3 and N_2O-emission mitigation practice (Hristov *et al.*, 2013). Low-protein diets for ruminants should be balanced for ruminally degradable protein in order not to impair microbial protein synthesis and fibre degradability in the rumen. Further, diets for all animals should be balanced for amino acids to avoid feed-intake depression and decreased production (Hristov *et al.*, 2013).

Housing

Structures used to house livestock animals do not directly affect the processes resulting in N_2O and CH_4 emissions; however, they determine the method used to store and process manure and eventual litter. Housing systems with solid floors that use hay or straw for bedding accumulate manure that has higher dry matter and is commonly stored in piles, creating conditions conducive for N_2O emissions. In general, manure systems in which manure is stored for prolonged periods of time produce greater NH_3 and CH_4 emissions compared with systems in which manure is removed daily. For example, Philippe *et al.* (2007) found that GHG emissions from fattening pigs raised on straw-based deep litter released nearly 20% more GHG emissions than when raised on a concrete slatted floor.

Hristov *et al.* (2012) assessed the effect of manure management on emissions from dairy farms in Pennsylvania and found that NH_3, and particularly CH_4, emissions from manure were much higher in dairy barns where manure was stored for prolonged periods of time (e.g. gravity-flow systems) than where manure was removed frequently (e.g. flush systems). Nitrous oxide emissions were negligible in all systems. In ruminant production, however, the effect of housing on CH_4 emissions is relatively marginal because the animal is the main source of CH_4 emission through eructation; N_2O emissions from ruminant housing are also usually negligible. Housing and manure systems, however, have a greater impact on NH_3 emission from cattle operations (Hristov *et al.*, 2013).

Biofiltration

Biofiltration can be performed on ventilated air from animal buildings. It uses biological filters to remove undesired elements (Hristov *et al.*, 2013). Melse and Ogink (2005) found NH_3 removal efficiencies in swine and poultry houses from acid scrubbers and biotrickling filters of 96% and 70%, respectively. However, recent reports (Maia *et al.*, 2012a and 2012b) have shown that biofilters used to scrub NH_3 from exhaust streams generate N_2O as a result of nitrification and denitrification processes in the biofiltration media. A few researchers have investigated CH_4 mitigation by passing contaminated air from above swine manure storage or from swine housing through a biofiltration system. A Canadian Pork Council (2006) study reported reductions of 50% to 60%, and Girard *et al.* (2011) reported a maximum reduction of up to 40%. High residence time is necessary in these systems because the low solubility and biodegradability of CH_4 hinder effectiveness (Melse and Verdoes, 2005).

Manure storage

Greenhouse gas emissions during manure storage, in the form of CH_4 (in anaerobic conditions), but also NH_3 and N_2O, can be significant. One simple way to avoid cumulative GHG emissions is to reduce the time manure is stored (Philippe *et al.*, 2007; Costa *et al.*, 2012). Covering manure stores is another common option to reduce losses. The effectiveness of the manure storage cover depends on many factors, including permeability, cover thickness, degradability, porosity and management (Hristov *et al.*, 2013).

Semi-permeable covers are valuable for reducing NH_3, CH_4 and odour (Sommer *et al.*, 2000; Guarino *et al.*, 2006; VanderZaag *et al.*, 2008); however, the net GHG effectiveness of semi-permeable manure storage covers is not clear, because they can provide conditions for nitrification, denitrification and subsequent release of N_2O emissions (Hansen *et al.*, 2009; Nielsen *et al.*, 2010). Conversely, impermeable covers are an effective mitigation practice, if the CH_4 captured under the cover is burned using a flare system or engine-generator to produce electricity (Hristov *et al.*, 2013).

Mechanical or intermittent aeration of manure during storage can also reduce CH_4 emissions (Osada, 2000; Martinez *et al.*, 2003; Loyon *et al.*, 2007), although mechanical aeration may lead to increased CO_2 emissions (Petersen and Sommer, 2011). Decreasing manure temperature to $<10°C$ by removing the manure from the building and storing it outside in cold climates can also mitigate CH_4 emissions (Monteny *et al.*, 2006).

According to Petersen and Sommer (2011), manure acidification is an effective mitigation option for NH_3 emissions, but the effect on N_2O is not well studied. Ndegwa *et al.* (2011) listed 15 studies in which cattle, pig or poultry manure NH_3 emissions were successfully mitigated (from 14% to 100%) by lowering manure pH. Although strong acids are cost-effective, weaker acids or acidifying salts are less hazardous and may therefore be more suitable for on-farm use (Hristov *et al.*, 2013).

Composting

Composting has several benefits related to manure handling, odour control, manure moisture and pathogen control, OM stabilization and farm profitability (Hristov *et al.*, 2013). The primary benefit of composting is that it reduces CH_4 emissions compared with storage of manure under anaerobic conditions (Brown *et al.*, 2008). However, depending on the intensity of composting, NH_3 losses can be particularly high, reaching up to 50% of the total manure N (Peigné and Girardin, 2004). Similarly, the aeration of compost reduces CH_4 emissions (Thompson *et al.*, 2004; Jiang *et al.*, 2011b; Park *et al.*, 2011), but can increase NH_3 and N_2O losses (Tao *et al.*, 2011). However, the review by Brown *et al.* (2008) concluded that, even in a worst-case scenario, the increase in N emissions is minimal in comparison with the benefits associated with the CH_4 reductions.

Anaerobic digestion

Anaerobic digestion is the process of degradation of organic material microorganisms in the absence of oxygen, producing CH_4, CO_2 and other gases as by-products, and is one of the most promising practices for mitigating GHG emissions from collected manure (Hristov *et al.*, 2013). Anaerobic digesters are also a source of renewable energy in the form of biogas, which is 60% to 80% CH_4, depending on the substrate and operation conditions (Roos *et al.*, 2004). However, NH_3 volatilization may be higher in digested manure (Petersen and Sommer, 2011). In contrast, reduction of manure OM content is generally expected to reduce N_2O emissions from manure-amended soils (Petersen, 1999; Bertora *et al.*, 2008), although there have been contradictory results (Thomsen *et al.*, 2010).

Digester designs vary widely in size, function and operational parameters. For a review of digester types and their comparative advantages in different production contexts (Hristov *et al.*, 2013). When CH_4 is collected and used as an energy source, it can substitute for combusted fossil fuels reducing the emissions of GHG, NOx, hydrocarbons and particulate matter (Börjesson and Berglund, 2006). However, CH_4 losses have been reported from stored manure gas leakages (Bjurling and Svärd, 1998; Sommer *et al.*, 2001). Typical losses from systems storing digested manure were reported to range from 5% to 20% of total biogas produced.

Overall, the use of anaerobic manure digesters is a strongly recommended CH_4-mitigation strategy, but careful management is necessary, so that they do not become net emitters of CH_4 (Hristov *et al.*, 2013). The adoption of this type of technology on farms of all sizes may not be widely applicable and will heavily depend on financial and technical capacity, climatic conditions and availability of alternative sources of energy.

Manure application

Results on CH_4 and N_2O emissions following manure application are highly variable, and many variables including manure composition, application technique, soil type and management, soil moisture and climate can affect emissions (Hristov *et al.*, 2013).

Subsurface injection of manure slurries into the soil can result in localized anaerobic conditions surrounding the buried liquid manure, which, together with an increased degradable C pool, may result in higher CH_4 emissions than with surface applied manure (Külling *et al.*, 2003; Amon *et al.*, 2006; Clemens *et al.*, 2006). Diluting the manure or reducing the degradable C flux through solid separation or anaerobic degradation pre-treatments are options to reduce CH_4 emissions from injected manure (Amon *et al.*, 2006; Clemens *et al.*, 2006). As this combination of treatments reduces the availability of degradable C, it also tends to decrease N_2O emission (Amon *et al.*, 2006; Clemens *et al.*, 2006; Velthof and Mosquera, 2011). However, both CH_4 and N_2O emissions resulting from manure injection into soil are generally low, and therefore should be weighed against the benefits of reducing NH_3 volatilization when manure is surface applied (Hristov *et al.*, 2013).

Unlike CH_4, most of the N_2O is produced after the manure has been applied to the soil. Nitrous oxide-mitigation options for manure application include controlling the amount of N available for nitrification and denitrification in soil, as well as the availability of degradable C and soil oxidation reduction potential (Hristov *et al.*, 2013). Wet soils tend to promote N_2O emissions, and therefore application timing (e.g. avoiding application before a rain event) can be important (Hernandez-Ramirez *et al.*, 2009; Smith and Owens, 2010; Meada *et al.*, 2011).

Manure deposition on pasture

The effective N-application rate within a urine patch from a dairy cow on pasture can be much greater than the utilization capacity of the soil–plant system (Eckard *et al.*, 2010). Nitrous oxide emissions from these systems can be reduced by creating a more uniform distribution of urine throughout the paddock.

Timing of grazing can also help, as De Klein *et al.* (2001) showed a 40% to 57% reduction in N_2O emissions when grazing was restricted to 3 h/day in the late humid New Zealand autumn. This reduction was attributed to diminished N input during conditions most conducive to N_2O emissions. However, when de Klein *et al.* (2001) included N_2O emissions resulting from application of the effluent collected during the restricted grazing periods, N_2O emissions were reduced by only 7% to 11%. It is also recognized that this practice results in much greater NH_3 emissions (Luo *et al.*, 2010) because of urine and faeces being excreted and allowed to mix in the stand-off/feed area.

Urease and nitrification inhibitors

Nitrification inhibitors were found to reduce the amount of N_2O emitted in intensive pasture-based systems in New Zealand when applied over urine and faeces that had been deposited on pastures and soil (de Klein *et al.*, 2001 and 2011; Di and Cameron, 2003 and 2012). Luo *et al.* (2008) reported up to 45% reduction in N_2O emissions from dairy cow urine applied to various soils in New Zealand by the dicyandiamide nitrification inhibitor (DCD). The effectiveness of the DCD nitrification inhibitors depends largely on temperature, moisture and soil type (Kelliher *et al.*, 2008; de Klein and Monaghan, 2011; Schils *et al.*, 2013). It should be noted that nitrification inhibitors can increase soil ammonium, and thus potentially increase NH_3 losses (Hristov *et al.*, 2013).

In contrast, urease inhibitors preserve urea and reduce NH_3 volatilization but may result in increased N_2O emissions because of potential increase in ammonium and subsequently nitrate concentration in soil (Hristov *et al.*, 2013). Further, as they need to be applied to urine before it is mixed with soil or faeces, its applicability is limited to systems where faeces and urine are not separated or separated after mixing (Varel *et al.*, 1999). Results of the combined use of nitrification and urease inhibitors have been inconclusive (Khalil *et al.*, 2009; Zaman and Blennerhassett, 2010).

Interactions and links with productivity

Interactions among individual components of livestock production systems are very complex, but must be considered when recommending GHG mitigation practices (Hristov *et al.*, 2013). One practice may successfully mitigate enteric CH_4 emission, but increase fermentable substrate for increased CH_4 emission from stored manure or N availability for increased N_2O emission from land application of manure. Some mitigation practices are synergistic and are expected to decrease both enteric and manure GHG emissions. This section outlines some of the main interactions that are reported in the literature. A summary of interactions to be considered for each mitigation practice is also proposed in Tables 1 and 2.

Feed, enteric methane, manure content and productivity

Starting with feed-based strategies, the cascade of synergistic and antagonistic effects that mitigation practices may trigger are discussed.

Feed additives and dietary manipulation options targeting enteric CH_4 emissions are mostly studied in isolation, but can have unexpected synergistic or antagonistic effects. It is unlikely that mitigation practices reviewed under the enteric CH_4 section can have additive effects, but there is not much evidence to support or refute this assumption (Hristov *et al.*, 2013). Nitrates can possibly increase N emissions as their addition to the ration may lead to increased urea excreted in urine. Dietary lipids too may increase manure emissions either through reduced ration digestibility or increased N content (if lipids are supplied from oil cakes rich in CP; Hristov *et al.*, 2013). Furthermore, if overadministered, feed additives can reduce animal productivity and thereby increase GHG Ei.

Dietary manipulation to increase nutrient digestibility is expected to decrease enteric CH_4 production and would most likely decrease GHG emissions from stored manure, because less-fermentable OM will be excreted with faeces (Hristov *et al.*, 2013). Feeding practices that stabilize rumen fermentation (in terms of pH) might also improve animal health and feed efficiency, and reduce GHG Ei by the animal or from manure storage. However, increased feed quality will generally result in an increased feed intake, which will in turn increase enteric CH_4 emissions (Hristov *et al.*, 2013). In addition, manure CH_4 emissions may also increase because of increased concentration of available substrate. This increase of emissions is, however, generally compensated by a greater increase in milk and meat output, resulting in a lower Ei (Hristov *et al.*, 2013). Yet, from a whole cycle perspective, this effect at farm level may be partially or entirely offset by greater emissions from the production of improved feed especially if land-use change (e.g. conversion of forests/grasslands to croplands) is involved. A side effect of increasing nutrient digestibility may be the oversupply of N to animals (e.g. in the case of pasture improvement/fertilization or urea treatment of by-products), resulting in higher N_2O emissions from manure (Hristov *et al.*, 2013). The overall effect will depend on initial conditions and strategies used to improve feed digestibility.

Decreasing dietary protein concentration to address NH_3 and N_2O losses from stored manure or manure-amended soil may increase enteric CH_4 emissions, as shown by the modelling work of Dijkstra *et al.* (2011b). Low-protein diets for ruminants should be balanced for ruminally degradable protein in order to not impair microbial protein synthesis and fibre degradability in the rumen. In general terms, reduction of dietary protein should be accompanied by a careful balancing for all other nutrients, specifically energy and amino acids, so that animal production is not negatively affected, which would result in an increased Ei (Hristov *et al.*, 2013).

Shifting N excretion from urine to faeces by supplementing the diet with tannins or feeding tanniferous forages can also decrease N release rate from manure, and thus affect manure-N availability for plant growth (Hristov *et al.*, 2013).

Manure storage, processing and application

The main interaction effects for manure management are between manure ammonium (NH_3) and soil N_2O emissions. In general, mitigation measures that reduce NH_3 losses in manure preserve ammonium N, and thereby increase potential soil N_2O emissions. Similarly, mitigation measures that aim to lower CH_4 emissions can also increase NH_3 or N_2O emissions.

However, the interactions involving N_2O and NH_3 need to be considered in light of the certainty with which the formation of each gas can be controlled. Because the conditions that support nitrification and denitrification processes are highly variable, N_2O emissions are best treated as potential emissions. By contrast, NH_3 emission and consequent N loss occur as a matter of course, though they also vary in magnitude depending on environmental and management factors (Hristov *et al.*, 2013).

Furthermore, the efficiency of practices that restrict NH_3 and N loss before (e.g. acidification and cooling) and during (e.g. manure injection into soil) application to soil very much depends on the degree of integration between crop and livestock enterprises. By increasing the availability of N for uptake by plants, these practices lower the need for external inputs of N fertilizer and their associated GHG emissions during their manufacture and following application to soil (Hristov *et al.*, 2013). Thus, the mitigation potential of such practices needs to be evaluated at least from a whole farm, or preferably a lifecycle, perspective.

Urease inhibitors can reduce NH_3 emissions, whereas nitrification inhibitors can reduce N_2O emissions. However, the timing of their use and impact of environmental conditions greatly affect their effectiveness and length of inhibition, with a delay rather than a reduction of NH_3 or N_2O emissions occurring under some conditions (Hristov *et al.*, 2013). In addition, the use of nitrification inhibitors could result in greater NH_3 emission following land application of manure because of greater accumulation of N as ammonium (Hristov *et al.*, 2013).

The fate of N_2O and NH_3 emissions is also affected by measures that seek to lower CH_4 emissions. For example, owing to interactions between available C and N sources in the correct oxidation form, semi-permeable manure storage covers can enhance N_2O formation (Hansen *et al.*, 2009; Nielsen *et al.*, 2010.

Decreasing storage time effectively reduces CH_4 emissions, because little further CH_4 emission occurs after land application of manure. However, the more frequent need for soil application may increase N_2O emissions, if application occurs during prolonged periods with warm temperature, wet soil and low plant-N uptake. Therefore, a combination of decreased storage time in warm weather and extended winter storage is a viable option in many regions (Hristov *et al.*, 2013).

Also with regard to manure application, the incorporation of manure into soil not only greatly reduces NH_3 emissions and N losses, but it also reduces CH_4 emissions and at the same time increases manure OM content. However, the increase in OM accelerates soil metabolism, depleting oxygen, triggering denitrification and N_2O emissions (Hristov *et al.*, 2013).

On the contrary, anaerobic digestion, or separation of manure solids, lowers the organic content of manure, which generally results in lower emissions of N_2O (Clemens *et al.*, 2006; Velthof and Mosquera, 2011). However, the inhibition of nitrification under anaerobic conditions can lead to greater ammonium N in digested manure, which, coupled with the pH increase that is likely with digestion, can lead to greater NH_3 emissions (Hristov *et al.*, 2013).

Composting is another measure where the mitigation consequences are confounded by interactions. Although composting tends to increase NH_3 emissions, its effect on CH_4 and N_2O emissions is more complex. However, the significant loss of NH_3 may lead to reduced soil N_2O emissions, and thus reduce total non-CO_2 GHG emissions from composted manure, compared with other manure management systems (Hristov *et al.*, 2013).

Conclusions

Many technical options exist for the mitigation of direct emissions from livestock production.

Diet manipulation and feed additives have been identified as main avenues for the mitigation of enteric CH_4 production. Their effectiveness is estimated to be generally low to medium but can be substantially increased in terms of Ei, when they also result in improved feed efficiency and productivity gains.

Diets also affect manure emissions, as they alter the content of manure: ration composition and additives have an influence on the form and amount of N in urine and faeces, as well as on the amount of fermentable OM in faeces.

Methane emissions from manure can be effectively controlled by shortening storage duration, ensuring aerobic conditions or capturing the biogas emitted in anaerobic conditions. Direct and indirect N_2O emissions are, however, much more difficult to prevent once N is excreted. Techniques that prevent emissions during initial stages of management preserve N in manure are often emitted at later stages. Thus, effective mitigation of N losses in one form (e.g. NH_3) is often offset by N losses in other forms (e.g. N_2O or NO_3). These induced effects must be understood when mitigation practices are designed. Numerous interactions were also highlighted between mitigation techniques for CH_4 and N_2O emissions from manure.

More research work is needed to develop practical and economically viable techniques that can be widely put into practice. Efforts should target single practices with high potential (e.g. vaccination against rumen methanogens) but also the interactions between practices, towards the development of suites of mitigation practices for specific production systems, based on the assessment of their overall effectiveness. In addition, research is required to quantify the economics of mitigation as well as the impact mitigation practices may have on other environmental objectives and broad development goals, such as poverty reduction and food security.

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