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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 CH4 emissions from enteric fermentation by ruminants, the largest single emission source from the global livestock sector, and for reducing CH4 and N2O 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 CH4 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

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 CH4 emissions from enteric fermentation by ruminants, the largest single emission source from the global livestock sector, and for reducing CH4 and N2O 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 CH4 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

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 benefited 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
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 CO2-eq, for the 2005 reference period (FAO, 2013a and 2013b). When considering only the direct CH4 and N2O emissions from enteric fermentation and manure (including its application), livestock are estimated to contribute 5.4 Gt CO2-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 CH4 and N2O 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 CO2-eq), poultry (0.7 Gt CO2-eq), buffalo (0.6 Gt CO2-eq) and small ruminants (0.5 Gt CO2-eq) (FAO, 2013a and 2013b).

Of the 3.3 Gt of direct cattle GHG emissions, CH4 from enteric fermentation is the largest source, accounting for a 71% share. Manure N2O, particularly from deposition on pasture, accounts for the next largest share (25%), whereas the remaining 4% is from manure CH4 (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 N2O) from feed production are almost equal in size to direct emissions. They represent 36% of cattle supply chain emissions, 60% of pork supply chain 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 CH4 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 CH4 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 CO2 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 CH4 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 CH4, are presented in Table 1.
<table>
<thead>
<tr>
<th>Mitigation technique</th>
<th>Effectiveness</th>
<th>Domain of relevance</th>
<th>Estimated emissions in domain of relevance (Mt CO₂-eq)</th>
<th>Interactions with other categories of emissions</th>
<th>Overall effectiveness, including interactions</th>
<th>Ei reduction through productivity enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed supplements</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dietary lipids</td>
<td>Medium</td>
<td>Confined and mixed ruminant systems of all regions</td>
<td>2319</td>
<td>Can reduce feed digestibility and this increases CH₄ from stored manure.</td>
<td>Yes, in the case of baseline diet with low energy content</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dairy cattle in grazing systems of North America, Europe, East Asia, Latin America and Oceania</td>
<td></td>
<td>If source is from oil seeds (e.g. cotton), then it can increase N content of feed, and thus of excreta. 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 &lt; 50%).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrate (electron receptor)</td>
<td>High</td>
<td>All ruminant systems, in all regions</td>
<td>2710</td>
<td>Potential toxicity. Potential increase in N₂O emissions from urine and manure, including deposition and application</td>
<td>Variable</td>
<td>None</td>
</tr>
<tr>
<td>Ionophores</td>
<td>Low</td>
<td>Confined beef production, outside EU27</td>
<td>124</td>
<td>Potential increase in N₂O emissions from urine and manure, including through manure deposition and application</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Tannins</td>
<td>Low</td>
<td>All ruminant systems, in all regions</td>
<td>2710</td>
<td>Decrease in urine-N and potential lower emission of N₂O</td>
<td>Yes</td>
<td>None or Ei increase</td>
</tr>
<tr>
<td>Feeds and feeding management</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Concentrate inclusion in diet</td>
<td>Low to medium (if inclusion levels &gt; 35%)</td>
<td>All ruminant confined and mixed systems, in all regions</td>
<td>2249</td>
<td>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 CH₄ emissions during storage. Higher-feed digestibility leads to lower replenishment of soil C through manure deposition and application.</td>
<td>Yes, if &gt;35 to 40%</td>
<td>Yes, even at low levels of inclusion</td>
</tr>
<tr>
<td>Improving forage quality</td>
<td>Low to medium</td>
<td>All ruminant systems, in all regions</td>
<td>2710</td>
<td>If CP content of diet exceeds protein requirement of animal, N₂O emissions may increase Increased digestibility can reduce CH₄ from stored manure. Can increase overall intake and thus increase enteric CH₄ 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.</td>
<td>Variable</td>
<td>Yes</td>
</tr>
</tbody>
</table>
### Table 1: Mitigation option for enteric methane emissions

<table>
<thead>
<tr>
<th>Mitigation technique</th>
<th>Effectiveness(^1)</th>
<th>Domain of relevance</th>
<th>Estimated emissions in domain of relevance (Mt CO(_2)-eq(^2))</th>
<th>Interactions with other categories of emissions</th>
<th>Overall effectiveness, including interactions</th>
<th>E(_i) reduction through productivity enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grazing management</td>
<td>Low to medium</td>
<td>All ruminant grazing and mixed systems, in all regions</td>
<td>2434</td>
<td>Variable</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Optimize productivity per ha, by maximizing digestible dry matter intake</td>
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<td></td>
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<td></td>
<td></td>
<td>Stocking rates may not be optimal for soil C.</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>If CP content of diet exceeds protein requirement of animal, N(_2)O emissions may increase</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>May have mitigation effect on N(_2)O emissions from manure application, and on CH(_4) emissions from stored manure</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Can increase NH(_3) emissions if urea is used. Can increase in feed intake</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed processing (grains)</td>
<td>Low</td>
<td>All ruminant confined and mixed systems, in all regions</td>
<td>2249</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Stocking rates may not be optimal for soil C.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkaline treatment</td>
<td>Low</td>
<td>All ruminant in mixed systems, in all regions</td>
<td>2132</td>
<td>Yes</td>
<td>No, emissions can increase</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Confined ruminant systems of Asia, Latin America, Sub Saharan Africa and Middle East/North Africa.</td>
<td></td>
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<td></td>
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<tr>
<td>Precision feeding</td>
<td>Low</td>
<td>All ruminant confined systems, in all regions</td>
<td>276</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Contributes to the reduction of manure CH(_4) and N(_2)O emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategic supplementation</td>
<td>Medium</td>
<td>All ruminant grazing systems, in all regions</td>
<td>2220</td>
<td>No, emissions can increase</td>
<td>Yes, can be substantial</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mixed systems in Eastern Europe, Asia, Latin America, Sub Saharan Africa and Middle East/North Africa.</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>Can increase feed intake (leading to higher absolute enteric CH(_4))</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increases N and volatile solids in manure, thus manure CH(_4) and N(_2)O emissions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)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 CH4 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 Eugene et al. (2011) reported that the combination of CH4 reductions and reduced dry matter intake (DMI) resulted in no difference in CH4 per unit of DMI, Rabiee et al. (2012) reported consistent reductions in CH4 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 CH4 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 CH4 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 CH4 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 CH4 production, but their potential effects on animal health are unclear. Other electron acceptors such as fumaric and malic acids may reduce CH4 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 CH4 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 CH4-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 CH4 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 CH4 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 CH4 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 CH4 emissions. Johnson and Johnson (1995) stated that CH4 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 CH4 production, with increased DMI, with the rate of ADG being greater for feeds of greater digestibility. Further, as the amount of CH4 released per unit of additional intake is greater for lower-digestibility feeds, the Ei of growth at any given DMI is less for digestible feeds. However, small changes in energy intake result in small changes in CH4 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 (Parsons et al., 2011). 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 (McCaughhey 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$_2$O and NH$_3$ are emitted, with the latter not being a GHG but potentially leading to indirect N$_2$O 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,
### Technical options for the mitigation of manure methane and nitrous oxide emissions, and their interactions with other categories of emissions

<table>
<thead>
<tr>
<th>Mitigation option</th>
<th>Effectiveness and targeted gas</th>
<th>Domain of relevance</th>
<th>Estimated manure CH₄ emissions in domain of relevance (Mt CO₂-eq)</th>
<th>Estimated manure N₂O emissions in domain of relevance (Mt CO₂-eq)²³</th>
<th>Main interactions with other categories of emission</th>
<th>Overall mitigation effect, including interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diet manipulation</td>
<td></td>
<td>All animals in all systems, except for monogastrics in backyard systems and ruminants in grazing systems of Asia, Sub-Saharan Africa and North Africa/Middle East</td>
<td>264</td>
<td>1222</td>
<td>Can increase overall intake and thus increase enteric CH₄ emissions in grazing and mixed systems</td>
<td>Yes</td>
</tr>
<tr>
<td>Balanced dietary protein</td>
<td>Medium (N₂O)</td>
<td>All ruminant systems in all regions</td>
<td>144</td>
<td>1237</td>
<td>Can lead to lower intake in high tannin browsers</td>
<td>None, emissions may increase</td>
</tr>
<tr>
<td>Tannins</td>
<td>Low (N₂O)</td>
<td>All ruminant systems in all regions</td>
<td>275</td>
<td>335</td>
<td>None observed</td>
<td>Yes</td>
</tr>
<tr>
<td>Housing system</td>
<td>High (CH₄ and N₂O)</td>
<td>All animals in all systems, except for grazing ruminants, all regions</td>
<td>133</td>
<td>80</td>
<td>Strong decrease of NH₃ emissions, leading to reduced indirect N₂O emissions. N₂O emissions can take place at disposal/maintenance of biofilter.</td>
<td>Variable</td>
</tr>
<tr>
<td>Biofiltration</td>
<td>Low (CH₄)</td>
<td>All animals in confined systems in all regions</td>
<td>275</td>
<td>335</td>
<td>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.</td>
<td>Variable</td>
</tr>
<tr>
<td>Manure storage</td>
<td>Decreased storage time</td>
<td>All animals in all systems, except for grazing ruminants, all regions</td>
<td>232</td>
<td>290</td>
<td>May also reduce NH₃ emissions</td>
<td>Yes if NH₃ is captured by plant, thus limiting N₂O emission at time of application</td>
</tr>
<tr>
<td>Natural or induced crust</td>
<td>High (CH₄)</td>
<td>All animals in confined and mixed systems, except for monogastrics in backyard systems, all regions</td>
<td>102</td>
<td>44</td>
<td>May increase N₂O emissions (thus increase in indirect N₂O emissions during application)</td>
<td>Variable</td>
</tr>
<tr>
<td>Sealed storage with flare</td>
<td>High (CH₄ and N₂O)</td>
<td>Ruminant in confined systems and monogastrics in intensive and intermediate systems, all regions</td>
<td>165</td>
<td>145</td>
<td>May increase N₂O emissions, including increase in indirect emissions from NH₃ losses High energy consumption can result in increase in CO₂ emissions Reduces indirect N₂O emissions from NH₃ losses but may cause increase in direct N₂O emissions.</td>
<td>Yes</td>
</tr>
<tr>
<td>Forced aeration</td>
<td>Medium to high (CH₄)</td>
<td>Monogastrics in intensive and semi-intensive systems North America, Latin America, Europe, East and South East Asia, Oceania</td>
<td>275</td>
<td>335</td>
<td>Increases NH₃ and N₂O emissions May contribute to increase in soil C through stabilization of organic matter Mechanized systems can be energy intensive, resulting in increased CO₂ emissions.</td>
<td>Yes</td>
</tr>
<tr>
<td>Manure acidification</td>
<td>Low (N₂O)</td>
<td>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</td>
<td>275</td>
<td>335</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitigation option</td>
<td>Effectiveness and targeted gas</td>
<td>Domain of relevance</td>
<td>Estimated manure CH4 emissions in domain of relevance (Mt CO2-eq)</td>
<td>Estimated manure N2O emissions in domain of relevance (Mt CO2-eq)</td>
<td>Main interactions with other categories of emission</td>
<td>Overall mitigation effect, including interactions</td>
</tr>
<tr>
<td>-------------------</td>
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<td>---------------------------------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>--------------------------------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>High (CH4)</td>
<td>All animals in all systems, except for grazing ruminants, all regions</td>
<td>275</td>
<td>335</td>
<td>May increase NH3 during storage and application of liquor Biogas generated can substitute fossil energy consumption.</td>
<td>Yes</td>
</tr>
<tr>
<td>Time of application</td>
<td>Low (CH4) to High (N2O)</td>
<td>All animals in all systems, except for grazing ruminants, all regions</td>
<td>not calculated (marginal)</td>
<td>435</td>
<td>May result in increase in NH3 losses May reduce N-fertilizer consumption (and related emissions) through better use of manure N</td>
<td>Yes</td>
</tr>
<tr>
<td>Standoff pads (Kraals)</td>
<td>Medium to high (N2O)</td>
<td>Ruminants in mixed and grazing systems, all regions</td>
<td>not calculated (marginal)</td>
<td>559</td>
<td>Can increase CH4 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</td>
<td>Variable</td>
</tr>
<tr>
<td>Nitrification inhibitor applied to pastures</td>
<td>High (N2O)</td>
<td>Ruminants in mixed and grazing systems. North America, Latin America, Europe, East and South East Asia, Oceania</td>
<td>not calculated (marginal)</td>
<td>318</td>
<td>Can result in higher NH3 emissions, depending on storage conditions and time prior to application Can increase pasture productivity and/or displace N fertilizer</td>
<td>Yes</td>
</tr>
<tr>
<td>Urease inhibitors applied at time of excretion/urination</td>
<td>Medium (N2O)</td>
<td>Ruminant in confined and mixed systems and monogastrics in intensive and intermediate systems, all regions</td>
<td>not calculated (marginal)</td>
<td>691</td>
<td>Reduces indirect N2O emissions from NH3 losses but may increase direct N2O and CH4 emissions</td>
<td>Unclear, emissions may increase</td>
</tr>
</tbody>
</table>

1Low = <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).
2Estimates based on FAO (2013a and 2013b).
3Includes 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$_2$O emissions from dairy manure (Külling et al., 2001; Aglé 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$_2$O 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$_2$O-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$_2$O 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$_2$O 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$_2$O 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$_2$O 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$_2$O, 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$_2$O 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 $<10^\circ$C by removing the manure from the building and storing it outside in cold
climates can also mitigate CH₄ emissions (Monteny et al., 2006).

According to Petersen and Sommer (2011), manure acidification is an effective mitigation option for NH₃ emissions, but the effect on N₂O is not well studied. Ndewa et al. (2011) listed 15 studies in which cattle, pig or poultry manure NH₃ 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 CH₄ emissions compared with storage of manure under anaerobic conditions (Brown et al., 2008). However, depending on the intensity of composting, NH₃ losses can be particularly high, reaching up to 50% of the total manure N (Peigne and Girardin, 2004). Similarly, the aeration of compost reduces CH₄ emissions (Thompson et al., 2004; Jiang et al., 2011b; Park et al., 2011), but can increase NH₃ and N₂O 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 CH₄ reductions.

Anaerobic digestion
Anaerobic digestion is the process of degradation of organic material microorganisms in the absence of oxygen, producing CH₄, CO₂ 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% CH₄ depending on the substrate and operation conditions (Roos et al., 2004). However, NH₃ volatilization may be higher in digested manure (Petersen and Sommer, 2011). In contrast, reduction of manure OM content is generally expected to reduce N₂O 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 CH₄ 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, CH₄ 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 CH₄-mitigation strategy, but careful management is necessary, so that they do not become net emitters of CH₄ (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 CH₄ and N₂O 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 CH₄ 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 CH₄ 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 N₂O emission (Amon et al., 2006; Clemens et al., 2006; Velthof and Mosquera, 2011). However, both CH₄ and N₂O emissions resulting from manure injection into soil are generally low, and therefore should be weighed against the benefits of reducing NH₃ volatilization when manure is surface applied (Hristov et al., 2013).

Unlike CH₄, most of the N₂O 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 N₂O 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 N₂O 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 N₂O emissions. However, when de Klein et al. (2001) included N₂O emissions resulting from application of the effluent collected during the restricted grazing periods, N₂O 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$_2$O 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$_2$O 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$_2$O 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$_2$O 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$_2$O 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$_2$O 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$_2$O emissions. In general, mitigation measures that reduce NH$_3$ losses in manure preserve ammonium N, and thereby increase potential soil N$_2$O emissions. Similarly, mitigation measures that aim to lower CH$_4$ emissions can also increase NH$_3$ or N$_2$O emissions.

However, the interactions involving N$_2$O 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
Mitigation of GHG emissions from livestock

highly variable, N₂O emissions are best treated as potential emissions. By contrast, NH₃ 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 NH₃ 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 NH₃ emissions, whereas nitrification inhibitors can reduce N₂O 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 NH₃ or N₂O emissions occurring under some conditions (Hristov et al., 2013). In addition, the use of nitrification inhibitors could result in greater NH₃ emission following land application of manure because of greater accumulation of N as ammonium (Hristov et al., 2013).

The fate of N₂O and NH₃ emissions is also affected by measures that seek to lower CH₄ emissions. For example, owing to interactions between available C and N sources in the correct oxidation form, semi-permeable manure storage covers can enhance N₂O formation (Hansen et al., 2009; Nielsen et al., 2010).

Decreasing storage time effectively reduces CH₄ emissions, because little further CH₄ emission occurs after land application of manure. However, the more frequent need for soil application may increase N₂O 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 NH₃ emissions and N losses, but it also reduces CH₄ emissions and at the same time increases manure OM content. However, the increase in OM accelerates soil metabolism, depleting oxygen, triggering denitrification and N₂O 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 N₂O (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 NH₃ emissions (Hristov et al., 2013).

Composting is another measure where the mitigation consequences are confounded by interactions. Although composting tends to increase NH₃ emissions, its effect on CH₄ and N₂O emissions is more complex. However, the significant loss of NH₃ may lead to reduced soil N₂O emissions, and thus reduce total non-CO₂ 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 CH₄ 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 N₂O 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. NH₃) is often offset by N losses in other forms (e.g. N₂O or NO₃). These induced effects must be understood when mitigation practices are designed. Numerous interactions were also highlighted between mitigation techniques for CH₄ and N₂O 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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Mitigation of GHG emissions from livestock


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