177
ISSN 0254-

FAO ANIMAL PRODUCTION AND HEALTH

paper

MITIGATION OF GREENHOUSE GAS EMISSIONS IN LIVESTOCK PRODUCTION

A review of technical options for non-CO_2 emissions

Cover photographs:

Left: ©WrenMedia/N. Palmer
Center: ©Dario Sabljak/Fotolia.com
Right: ©FAO/Thomas Hug

177

FAO ANIMAL PRODUCTION AND HEALTH
paper

MITIGATION OF GREENHOUSE GAS EMISSIONS IN LIVESTOCK PRODUCTION

A review of technical options for non-CO_2 emissions

Editors
Pierre J. Gerber, Benjamin Henderson and Harinder P.S. Makkar

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2013

Authors' details

Alexander N. Hristov[1*], Joonpyo Oh[1], Chanhee Lee[1], Robert Meinen[1], Felipe Montes[1], Troy Ott[1], Jeff Firkins[2], Al Rotz[3], Curtis Dell[3], Adegbola Adesogan[4], WenZhu Yang[5], Juan Tricarico[6], Ermias Kebreab[7], Garry Waghorn[8], Jan Dijkstra[9] and Simon Oosting[9]

[1] Pennsylvania State University, University Park, PA 16802, USA
[2] The Ohio State University, Columbus OH 43210, USA
[3] USDA-Agricultural Research Service, Pasture Systems and Watershed Management Research Unit, University Park, PA 16802, USA
[4] University of Florida, Gainesville, FL 32608, USA
[5] Agriculture and Agri-Food Canada, Lethbridge AB, Canada T1J 4B1
[6] Innovation Center for U.S. Dairy, Rosemont, IL 60018, USA
[7] University of California, Davis, CA 95616, USA
[8] DairyNZ, Hamilton 3240, New Zealand
[9] Wageningen University, 6700 AH Wageningen, The Netherlands
* Correspondence: anh13@psu.edu; pierre.gerber@fao.org

Advisory group

Michel Doreau (INRA/VetAgro Sup, Herbivores Unit, 63122 Saint-Genès Champanelle, France); Richard Eckard; Mario Herrero; Dong Hongmin; Tim McAllister (Agriculture and Agri-Food Canada); Hayden Montgomery; Kurt Roos; Sven G. Sommer; Markos Tibbo (Livestock Officer, UN-FAO Regional Office for the Near East, Cairo, Egypt); J. Mark Powell (United States Department of Agriculture, Agricultural Research Service).

Recommended citation

Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J. & Oosting, S. 2013. *Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO_2 emissions.* Edited by Pierre J. Gerber, Benjamin Henderson and Harinder P.S. Makkar. FAO Animal Production and Health Paper No. 177. FAO, Rome, Italy.

Acknowledgement

The Mitigation of Climate Change in Agriculture (MICCA) project provided financial and technical contributions to this publication.

ISBN 978-92-5-107658-3 (print)
E-ISBN 978-92-5-107659-0 (PDF)

Contents

FIGURES

TABLES

Editors' preface

This report presents a unique and exhaustive review of current knowledge on mitigation practices for greenhouse gas emissions in the livestock sector. It focuses specifically on non-CO_2 emissions from enteric fermentation and manure management.

The need for this review was prompted by the lack of comprehensive, science-based, and consolidated information on existing greenhouse gas mitigation practices applicable to different livestock production systems across the globe. It is part of a stream of activities being carried out by FAO to identify low greenhouse gas emission pathways for the livestock sector.

The report references over 900 publications on the mitigation of direct nitrous oxide and methane emissions and highlights the most promising options, given their demonstrated effectiveness and feasibility for adoption. The review was deliberately limited to in vivo experiments to reflect what can be achieved with available mitigation practices.

This in-depth assessment will inform the livestock industry, academia, governmental and non-governmental organizations that are interested in identifying and designing mitigation interventions for the sector. It will also help to identify research and development priorities in the area.

Importantly, the report provides the initial, but crucial, information needed to conduct broader and more quantitative analyses. This review focuses on single mitigation practices, however, the effectiveness of practices can enhanced when they are combined into packages of interventions, tailored to the production system and its environment. Designing emission reduction interventions for the sector also requires a detailed understanding of their effect on factors such as production costs, competitiveness and risks incurred by stakeholders along the supply chain, but also of their impact on other environmental goods and services such as water resources or biodiversity. This broader analysis will help to craft interventions that can deliver multiple societal objectives of the sector, which include food security, poverty reduction, economic development and environmental sustainability.

For practical reasons, the review focuses on direct emissions, taking place at the livestock producer level. The reduction of emissions taking place upstream (e.g. feed production) and downstream (e.g. processing and transport) of the livestock producer were excluded, although they can account for a large share of the total supply chain emissions, especially for monogastric species. Carbon dioxide emissions, which are mostly related to land use and land use change, but also to energy consumption, were also excluded from the scope of this review. There are sizeable mitigation opportunities among these emission sources, although their quantification remains challenging.

The review was carried out by a team of experts who collated, analysed and synthesized the literature on non-CO_2 greenhouse gas mitigation practices. An advisory group provided feedback and broaden the knowledge base of the review. Together with FAO staff, the two groups assessed the identified mitigation practices and elaborated on the potential interactions among practices during a peer review workshop.

While originally developed for internal purposes, this wide ranging state of the art review was felt to be a valuable resource for other groups also committed to addressing the sector's emissions, and has accordingly been prepared for wider dissemination.

Pierre J. Gerber, Benjamin Henderson, Harinder P.S. Makkar

Abstract

Animal production is a significant source of greenhouse gas (GHG) emissions worldwide. Depending on the accounting approaches and scope of emissions covered, estimates by various sources (IPCC, FAO, EPA or others) place livestock contribution to global anthropogenic GHG emissions at between 7 and 18 percent. The current analysis was conducted to evaluate the potential of nutritional, manure and animal husbandry practices for mitigating methane (CH_4) and nitrous oxide (N_2O) – i.e. non-carbon dioxide (non-CO_2) – GHG emissions from livestock production. These practices were categorized into enteric CH_4, manure management and animal husbandry mitigation practices. Emphasis was placed on enteric CH_4 mitigation practices for ruminant animals (only *in vivo* studies were considered) and manure mitigation practices for both ruminant and monogastric species. Over 900 references were reviewed; and simulation and life cycle assessment analyses were generally excluded.

In evaluating mitigation practices, the use of proper units is critical. Expressing enteric CH_4 energy production on gross energy intake basis, for example, does not accurately reflect the potential impact of diet quality and composition. Therefore, it is noted that GHG emissions should be expressed on a digestible energy intake basis or per unit of animal product (i.e. GHG emission intensity), because this reflects most accurately the effect of a given mitigation practice on feed intake and the efficiency of animal production.

ENTERIC CH_4 MITIGATION PRACTICES

Increasing forage digestibility and digestible forage intake will generally reduce GHG emissions from rumen fermentation (and stored manure), when scaled per unit of animal product, and are highly-recommended mitigation practices. For example, enteric CH_4 emissions may be reduced when corn silage replaces grass silage in the diet. Legume silages may also have an advantage over grass silage due to their lower fibre content and the additional benefit of replacing inorganic nitrogen fertilizer. Effective silage preservation will improve forage quality on the farm and reduce GHG emission intensity. Introduction of legumes into grass pastures in warm climate regions may offer a mitigation opportunity, although more research is needed to address the associated agronomic challenges and comparative N_2O emissions with equivalent production levels from nitrogen fertilizer.

Dietary lipids are effective in reducing enteric CH_4 emissions, but the applicability of this practice will depend on its cost and its effects on feed intake, production and milk composition. High-oil by-product feeds, such as distiller's grains, may offer an economically feasible alternative to oil supplementation as a mitigation practice, although their higher fibre content may have an opposite effect on enteric CH_4, depending on basal diet composition. Inclusion of concentrate feeds in the diet of ruminants will likely decrease enteric CH_4 emissions per unit of animal product, particularly when above 40 percent of dry matter intake. The effect may depend on type of 'concentrate' inclusion rate, production response, impact on fibre digestibility, level of nutrition, composition of the basal diet and feed processing.

Supplementation with small amounts of concentrate feed is expected to increase animal productivity and decrease GHG emission intensity when added to all-forage diets. However, concentrate supplementation should not substitute high-quality forage. Processing of grain to increase its digestibility is likely to reduce enteric CH_4 emission intensity. Nevertheless, caution should be exercised so that concentrate supplementation and processing does not compromise digestibility of dietary fibre. In many parts of the world, concentrate inclusion may not be an economically feasible mitigation option. In these situations improving the nutritive value of low-quality feeds in ruminant diets can have a considerable benefit on herd productivity, while keeping the herd CH_4 output constant or even decreasing it. Chemical treatment of low-quality feeds, strategic supplementation of the diet, ration balancing and crop selection for straw quality are effective mitigation strategies, but there has been little adoption of these technologies.

Nitrates show promise as enteric CH_4 mitigation agents, particularly in low-protein diets that can benefit from nitrogen supplementation, but more studies are needed to fully understand their impact on whole-farm GHG emissions, animal productivity and animal health. Adaptation to these compounds is critical and toxicity may be an issue. Through their effect on feed efficiency, ionophores are likely to have a moderate CH_4 mitigating effect in ruminants fed high-grain or grain-forage diets. However, regulations restrict the availability of this mitigation option in many countries. In ruminants on pasture, the effect of ionophores is not sufficiently consistent for this option to be recommended as a mitigation strategy. Tannins may also reduce enteric CH_4 emissions, although intake and milk production may be compromised. Further, the agronomic characteristics of tanniferous forages must be considered when they are discussed as a GHG mitigation option. There is not sufficient evidence that other plant-derived bioactive compounds, such as essential oils, have a CH_4-mitigating effect. Some direct-fed microbials, such as yeast-based products, might have a moderate CH_4-mitigating effect through increasing animal productivity and feed efficiency, but the effect is expected to be inconsistent. Vaccines against rumen archaea may offer mitigation opportunities in the future, although the extent of CH_4 reduction appears small, and adaptation and persistence of the effect is unknown.

MANURE MANAGEMENT MITIGATION PRACTICES

Diet can have a significant impact on manure (faeces and urine) chemistry and therefore on GHG emissions during storage and following land application. Manure storage may be required when animals are housed indoors or on feedlots, but a high proportion of ruminants are grazed on pastures or rangeland, where CH_4 emissions from their excreta is very low and N_2O losses from urine can be substantial. Decreased digestibility of dietary nutrients is expected to increase fermentable organic matter concentration in manure, which may increase manure CH_4 emissions. Feeding protein close to animal requirements, including varying dietary protein concentration with stage of lactation or growth, is recommended as an effective manure ammonia and N_2O emission mitigation practice. Low-protein diets for ruminants should be balanced for rumen-degradable protein so that microbial protein synthesis and fibre degradability are not impaired. Decreasing total dietary protein and supplementing the diet with synthetic amino acids is an effective ammonia and N_2O mitigation strategy for non-ruminants. Diets for all species should be balanced for amino acids to avoid feed intake depression and decreased animal productivity. Restricting grazing when conditions are most favourable for N_2O formation, achieving a more uniform distribution of urine on soil and optimizing fertilizer application are possible N_2O mitigation options for ruminants on pasture. Forages with higher sugar content (high-sugar grasses or forage harvested in the afternoon when its sugar content is higher) may reduce urinary nitrogen excretion, ammonia volatilization and perhaps N_2O emission from manure applied to soil, but more research is needed to support this hypothesis. Cover cropping can increase plant nitrogen uptake and decrease accumulation of nitrate, and thus reduce soil N_2O emissions, although the results have not been conclusive. Urease and nitrification inhibitors are promising options to reduce N_2O emissions from intensive livestock production systems, but can be costly to apply and result in limited benefits to the producer.

Overall, housing, type of manure collection and storage system, separation of solids and liquid and their processing can all have a significant impact on ammonia and GHG emissions from animal facilities. Most mitigation options for GHG emissions from stored manure, such as reducing the time of manure storage, aeration, and stacking, are generally aimed at decreasing the time allowed for microbial fermentation processes to occur before land application. These mitigation practices are effective, but their economic feasibility is uncertain. Semi-permeable covers are valuable for reducing ammonia, CH_4 and odour emissions at storage, but are likely to increase N_2O emissions when effluents are spread on pasture or crops. Impermeable membranes, such as oil layers and sealed plastic covers, are effective in reducing gaseous emissions but are not very practical. Combusting accumulated CH_4 to produce electricity or heat is recommended. Acidification (in areas where soil acidity is not an issue) and cooling are further effective methods for reducing ammonia and CH_4 emissions from stored manure. Composting can effectively reduce CH_4 but can have a variable effect on N_2O emissions and increases ammonia and total nitrogen losses.

Anaerobic digesters are a recommended mitigation strategy for CH_4 generate renewable energy, and provide sanitation opportunities for developing countries, but their effect on N_2O emissions is unclear. Management of digestion systems is important to prevent them from becoming net emitters of GHG. Some systems require high initial capital investments and, as a result, their adoption may occur only when economic incentives are offered. Anaerobic digestion systems are not recommended for geographic locations with average temperatures below 15 °C without supplemental heat and temperature control.

Lowering nitrogen concentration in manure, preventing anaerobic conditions and reducing the input of degradable manure carbon are effective strategies for reducing GHG emissions from manure applied to soil. Separation of manure solids and anaerobic degradation pre-treatments can mitigate CH_4 emission from subsurface-applied manure, which may otherwise be greater than that from surface-applied manure. Timing of manure application (e.g. to match crop nutrient demands, avoiding application before rain) and maintaining soil pH above 6.5 may also effectively decrease N_2O emissions.

ANIMAL HUSBANDRY MITIGATION PRACTICES

Increasing animal productivity can be a very effective strategy for reducing GHG emissions per unit of livestock product. For example, improving the genetic potential of animals through planned cross-breeding or selection within breeds, and achieving this genetic potential through proper nutrition and improvements in reproductive efficiency, animal health and reproductive lifespan are effective and recommended approaches for improving animal productivity and reducing GHG emission intensity. Reduction of herd size would increase feed availability and productivity of individual animals and the total herd, thus lowering CH_4 emission intensity. Residual feed intake may be an appealing tool for screening animals that are low CH_4 emitters, but currently there is insufficient evidence that low residual feed intake animals have a lower CH_4 yield per unit of feed intake or animal product. However, selection for feed efficiency will yield animals with lower GHG emission intensity. Breed difference in feed efficiency should also be considered as a mitigation option, although insufficient data are currently available on this subject. Reducing age at slaughter of finished cattle and the number of days that animals are on feed in the feedlot by improving nutrition and genetics can also have a significant impact on GHG emissions in beef and other meat animal production systems.

Improved animal health and reduced mortality and morbidity are expected to increase herd productivity and reduce GHG emission intensity in all livestock production systems. Pursuing a suite of intensive and extensive reproductive management technologies provides a significant opportunity to reduce GHG emissions. Recommended approaches will differ by region and species, but will target increasing conception rates in dairy, beef and buffalo, increasing fecundity in swine and small ruminants, and reducing embryo wastage in all species. The result will be fewer replacement animals, fewer males required where artificial insemination is adopted, longer productive life and greater productivity per breeding animal.

CONCLUSIONS

Overall, improving forage quality and the overall efficiency of dietary nutrient use is an effective way of decreasing GHG emissions per unit of animal product. Several feed supplements have a potential to reduce enteric CH_4 emission from ruminants, although their long-term effect has not been well-established and some are toxic or may not be economically viable in developing countries. Several manure management practices have a significant potential for decreasing GHG emissions from manure storage and after application or deposition on soil. Interactions among individual components of livestock production systems are very complex, but must be considered when recommending GHG mitigation practices. One practice may successfully mitigate enteric CH_4 emission, but increase fermentable substrate for increased GHG emissions from stored or land-applied manure. Some mitigation practices are synergistic and are expected to decrease both enteric and manure GHG emissions (for example, improved animal health and animal productivity). Optimizing animal productivity can be a very successful strategy for mitigating GHG emissions from the livestock sector in both developed and developing countries.

Abbreviations and acronyms

AA	amino acid
Ac:Pr	acetate:propionate ratio
ADF	acid detergent fibre
ADG	average daily gain
AI	artificial insemination
AR	all ruminants
AS	all species
BAC	bioactive compounds
BC	beef cattle
BCM	bromochloromethane
BES	2-bromo-ethane sulfonate
BMR	brown mid-rib corn
BW	body weight
C	carbon
CAB	Commonwealth Agricultural Bureau
CC	continuous culture
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CP	crude protein
DC	dairy cattle
DCD	dicyandiamide (nitrification inhibitor)
DDG	dried distiller’s grain
DDGS	dried distiller’s grain with solubles
DE	digestible energy
DEFRA	Department for Environment, Food and Rural Affairs, United Kingdom
DEI	digestible energy intake
DFM	direct-fed microbials
DGGE	denaturing gradient gel electrophoresis
DM	dry matter

DMI	dry matter intake
DPR	daughter pregnancy rate
ECM	energy-corrected milk
EE	ether extract
Ei	emission intensity
EIT	economies in transition
EPA	Environmental Protection Agency (United States)
Eq	equivalents
EXE	exogenous enzyme
FA	fatty acid
FAO	Food and Agriculture Organization of the United Nations
FCM	fat-corrected milk
FPCM	fat and protein-corrected milk
FecB gene	Boorola Merino fecundity gene
FMA	fumaric and malic acid
GE	gross energy
GEI	gross energy intake
GHG	greenhouse gas (in this document, GHG refers primarily to CH_4 and N_2O)
GO	goats
Gt	gigatonnes
GWP	global warming potential
$[H_2](aq)$	aqueous-phase H_2 concentration
H_2 (H)	hydrogen
HSG	high-sugar grasses
IOFC	income-over-feed cost
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessment
LI	level of intake
ME	metabolizable energy
MNE	milk nitrogen efficiency
MP	metabolizable protein
MSDS	material safety data sheets
Mt	million tonnes
N	nitrogen

NDF	neutral-detergent fibre
NE	not effective
NH_3	ammonia
NIRS	near-infrared reflectance spectroscopy
NK	effect not known
N_2OR	N_2O reductase
N_2O	nitrous oxide
NPN	non-protein N
NOx	nitrogen dioxide
OECD	Organisation for Economic Co-operation and Development
OM	organic matter
OMD	organic matter digestibility
P	phosphorus
PBAC	plant bioactive compound
PCR	polymerase chain reaction
PL	productive life
PO	poultry
rbST	recombinant bovine somatotropin
RDP	ruminally-degradable protein
rRNA	ribosomal ribonucleic acid
RUP	ruminally-undegradable protein
RFI	residual feed intake
SBM	soybean meal
SD	standard deviation
SE	standard error
SEA	South and Southeast Asia
SEM	standard error of the mean
SF_6	sulphur hexafluoride
SH	sheep
St	starch
SW	swine
TAN	total ammoniacal nitrogen
TDN	total digestible nutrients
TMR	total mixed ration

USDA	United States Department of Agriculture
UV	ultraviolet
VE	very effective
VFA	volatile fatty acid
WDG	wet dried distiller's grain
WDGS	wet distiller's grain with solubles
$\mathbf{Y_m}$	CH_4 energy emitted as percent of GE ingested
YP	yeast-based product

Introduction

LIVESTOCK GLOBAL NON-CO_2 GREENHOUSE GAS EMISSIONS

Unquestionably, the livestock sector represents a significant source of greenhouse gas (GHG) emissions worldwide, generating carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) throughout the production process. Livestock contribute to climate change by emitting GHG either directly (e.g. from enteric fermentation and manure management) or indirectly (e.g. from feed-production activities and conversion of forest into pasture). Based on a life cycle assessment (LCA) approach, it was estimated that the sector emits about 7.1 Gt of CO_2-eq, or about 18 percent of total global anthropogenic GHG emissions (Steinfeld *et al.*, 2006).

Steinfeld *et al.* (2006) have estimated major sources of emissions along livestock supply chains as follows (figures under revision):

- Land use and land-use change: 2.5 Gt CO_2-eq, including forest and other natural vegetation replaced by pasture and feed crop in the Neotropics (CO_2) and carbon (C) release from soils, such as pasture and arable land dedicated to feed production (CO_2);
- Feed production (except C released from soil): 0.4 Gt CO_2-eq, including fossil fuel used in manufacturing chemical fertilizer for feed crops (CO_2) and chemical fertilizer application on feed crops, and leguminous feed crops (N_2O);
- Animal production: 1.9 Gt CO_2-eq, including enteric fermentation from ruminants (CH_4) and on-farm fossil fuel use (CO_2);
- Manure management: 2.2 Gt CO_2-eq, mainly through manure storage, application and deposition (CH_4, N_2O);
- Processing and international transport: 0.03 Gt CO_2-eq.

The Intergovernmental Panel on Climate Change estimates (IPCC, 2007) follow a different attribution procedure, placing global anthropogenic GHG emissions from agriculture at 5.1 to 6.1 Gt CO_2-eq /yr in 2005 (or 10 to 12 percent of the total) and at over 30 percent when land use and land-use change is included (Smith *et al.*, 2007a).

Based on a report by the US Environmental Protection Agency (EPA, 2006) the direct livestock contribution to global non-CO_2 emissions, i.e. CH_4 and N_2O, can be calculated. According to the report, global enteric CH_4 emissions were estimated/predicted at 2 079 and 2 344 Mt CO_2-eq/yr for 2010 and 2020, respectively; and CH_4 emissions from manure storage were estimated at 470 and 523 Mt CO_2-eq/yr, respectively. Meanwhile, emissions of N_2O from various cropping practices (including emissions from fertilizers and manure application and deposition by grazing livestock) were estimated at 2 482 and 2 937 Mt CO_2-eq/yr, respectively.

The report did not specify how much of the soil N_2O emissions would be from manure, but these were estimated at about 48 percent of the total livestock N_2O emissions (excluding manure storage) by O'Mara (2011), which would amount to 1 191 and 1 410 Mt CO_2-eq/yr, respectively, based on the aggregate soil N_2O emission estimate in the EPA report.

Thus, based on EPA (2006) data, the total direct, non-CO_2 GHG emissions from livestock totalled 3 740 and 4 277 Mt CO_2-eq/yr for 2010 and 2020. When IPCC data (IPCC, 2007) for total GHG emissions are projected to 2010 and 2020 (a linear relationship; $r^2 = 0.98$), according to the EPA (2006) report the direct, non-CO_2 emissions from livestock contribute about 7.3 to 7.5 percent of global GHG emissions in 2010 and 2020, respectively. Others have estimated the contribution of animal agriculture to global GHG emissions at 8 to 11 percent (O'Mara, 2011).

According to estimates for the United States (EPA, 2011), livestock accounted for about 3.1 percent of the total GHG emission in 2009, but was the second largest emitter of CH_4 (28 percent of the total emission) and animal manure was the third largest source of N_2O (6 percent of the total emission). Both gases are powerful GHG with a global warming potential (GWP) of 25 and 298 CO_2-eq (kg/kg; Solomon *et al.*, 2007). In pasture-based animal systems in countries with a large agricultural sector, such as Argentina and New Zealand, the contribution of livestock to GHG emissions is considerably greater (Leslie *et al*., 2008; O'Mara, 2011).

The main processes contributing to direct non-CO_2 GHG emissions from livestock are: enteric fermentation and manure decomposition. These processes are the largest sources of CH_4 and N_2O from any animal production system and are the areas of emphasis in this document.

Life cycle assessments of various livestock systems have shown that on-farm emissions represent the largest contribution to the C footprint of dairy or beef supply chains (Roy *et al.*, 2009; Beauchemin *et al.*, 2010; Peters *et al.*, 2010; FAO, 2010; Kristensen *et al.*, 2011; Thoma *et al.*, 2013; Figure 1).

> *Thus, the ruminant animal and its gaseous emissions (enteric or from manure) should be the primary targets of a successful GHG mitigation programme.*

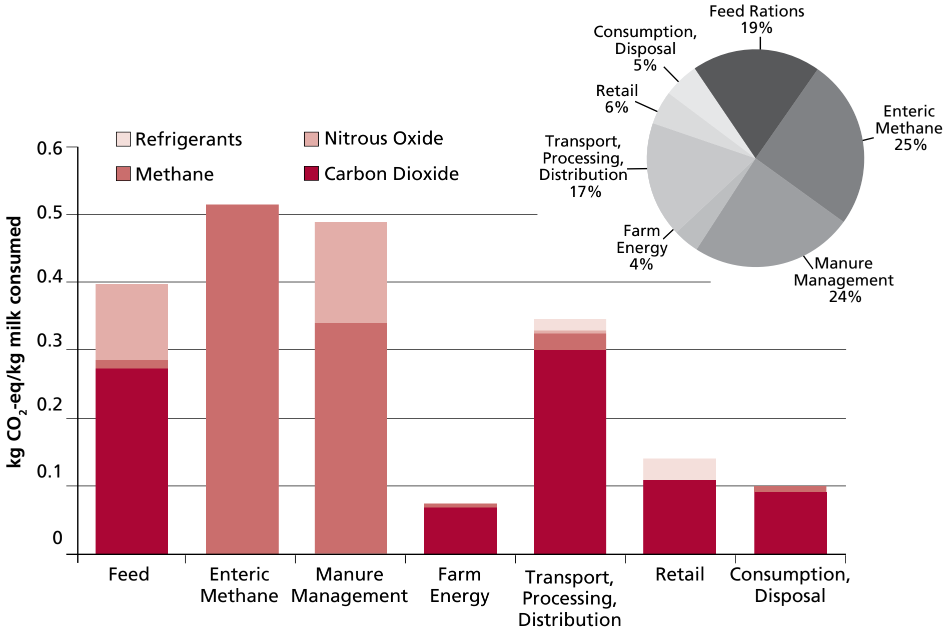
Similarly, the animal is the main contributor to GHG emissions in the swine industry. An LCA of the United States pork industry reported the following breakdown of emission contributions for each stage of the production cycle: 9.6 percent, sow barn (including feed and manure handling); 52.5 percent, nursery to finish (including feed and manure handling); 6.9 percent, processing (5.6 percent) and packaging (1.3 percent); 7.5 percent, retail (electricity and refrigerants); and 23.5 percent, the consumer (refrigeration, cooking and CH_4 from food waste in landfills) (Thoma *et al.*, 2011).

Major sources of GHG emissions in the poultry industry can be quite different depending on the type of production. An LCA of the United States poultry industry found that in the broiler house, excluding feed, 91 percent of the emissions are mechanical (purchased electricity, mobile and stationary machinery) and only 9 percent non-mechanical (enteric fermentation and manure management). In a breeder house, however, 66 percent of the GHG emissions were reported as non-mechanical vs 35 percent as mechanical (Dunkley, 2012).

Relative to ruminants, however, monogastric animals are minor emitters of GHG. The IPCC (2006a) assumes enteric CH_4 emission factors for pigs at about 1.2 to 2.8 percent of the emission factors for cattle [1.5 vs 53 (beef or growing cattle) or 128 kg CH_4/head per year (high-producing North American dairy cow)]. Recent estimates place GHG emissions

FIGURE 1

Supply chain contribution to carbon footprint of 'generic' milk in the U.S.



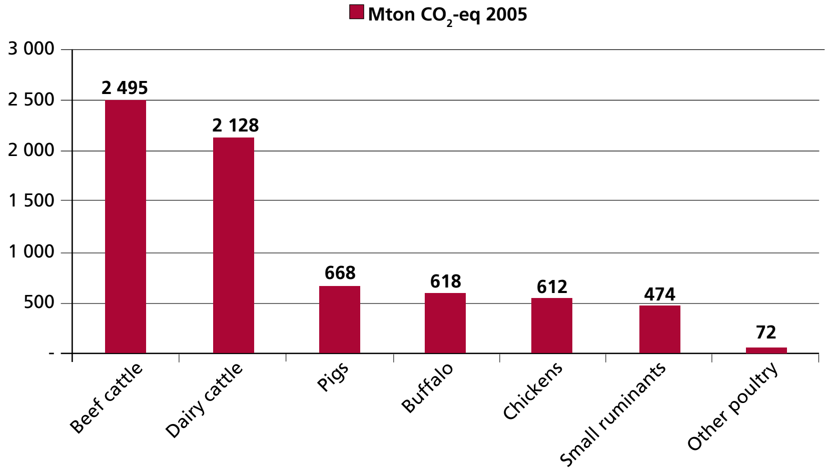
Source: Thoma *et al.*, 2013.

from pigs at about 9.5 percent of the total emissions from livestock (Gerber *et al.*, 2012) and, according to the same authors, the contribution of poultry to the global livestock GHG emissions is around 9.7 percent (Figure 2).

Domestic non-ruminant herbivore animals (horses, donkeys, mules, hinnies) produce enteric CH_4 as a result of fermentation processes in their hindgut. As discussed in the following section, however, hindgut fermenters do not produce as much CH_4 per unit of fermented feed as ruminants, perhaps as a result of availability of hydrogen sinks other than CH_4 (Jensen, 1996). The IPCC (2006a) assumes enteric CH_4 emissions from horses at 18 kg/head per year (compared with 128 kg for a high-producing dairy cow of similar BW). With the world horse population standing at around 58.8 million (FAOSTAT, 2010), global enteric CH_4 emissions from horses can be estimated at about 1.1 Mt CH_4/yr. Assuming a GWP of CH_4 at 25, enteric CH_4 emissions from horses represent 26.5 Mt CO_2-eq/yr, which is around 0.6 percent of the global GHG emissions from cattle (based on Gerber *et al.*, 2012).

Methanogenic archaea inhabit the digestive system and have been isolated from faeces of many monogastric and non-ruminant herbivore animals (Jensen, 1996). In these species, CH_4 is formed by processes similar to those occurring in the rumen and is similarly increased by intake of fibrous feeds (Jensen, 1996). As pointed out by Jensen (1996), however, in pigs and perhaps other monogastric species, CH_4 formation is not the only hydrogen sink and measured CH_4 production is considerably lower than stoichiometric estimates. Summarizing published data, Jensen (1996) estimated that a 100-kg pig produces about 4.3

FIGURE 2
Total emissions from the global livestock sector, by main animal species and commodities



Source: Gerber *et al.,* 2012.

percent of the daily CH_4 emission of a 500-kg cow (0.10 vs 0.46 L CH_4/day per kg of BW, respectively). Herbivore animals, like the horse, consume primarily fibrous feeds and emit greater amounts of CH_4 than monogastric species consuming primarily non-fibrous diets, but their CH_4 production per unit of BW is still significantly lower than that of ruminants (0.16 vs 0.46 L CH_4/day per kg of BW, according to Jensen, 1996).

Wild animals, specifically ruminants, also emit CH_4 from enteric fermentation in their complex stomachs or in the lower guts (Crutzen *et al.*, 1986; Jensen, 1996; Galbraith *et al.*, 1998; Kelliher and Clark, 2010). The present-day contribution of wild ruminants to the global GHG emissions is relatively low. Crutzen *et al.* (1986) proposed that global CH_4 emissions from wild ruminants represent from 2.5 to 7.7 percent (2 to 6 Tg/yr) of the total CH_4 emissions from domestic and wild animals (78 Tg/yr). Enteric CH_4 emissions for wild ruminants (bison, elk, and deer) for the contiguous U.S. were estimated at about 6 Tg CO_2-eq/yr, or 4.3 percent of the emissions from domestic ruminants (Hristov, 2012). In the pre-settlement period, however, wild ruminants in the contiguous U.S. emitted from 62 to 154 Tg CO_2-eq/yr, depending on the assumed size of the bison population, which is on average about 86 percent of the present-day CH_4 emissions from domestic ruminants in the U.S. (Hristov, 2012). Kelliher and Clark (2010) also estimated similar historic bison and contemporary cattle enteric CH_4 emissions for the North American Great Plains.

In the global context, particular attention must be placed on mitigating GHG emissions from developing countries. According to the 2007 IPCC report, about 70 percent of the global technical mitigation potential from agriculture lies in non-OECD (Organisation for Economic Co-operation and Development)/EIT (economies in transition; former Soviet Union and Eastern Europe) countries, 20 percent in OECD countries (i.e. mostly developed

photo 1
Beef feedyard in the Texas Panhandle, United States

AGRICULTURAL RESEARCH SERVICE/N. A. COLE

countries), and 10 percent in EIT countries (Smith *et al.*, 2007a). The U.S. Environmental Protection Agency (2006) estimates for 1990-2020 projected greater rates of total GHG emissions increase in developing countries of the Middle East, Africa, Latin America, South-east and East Asia (growth rates of 197, 104, 86, 64 and 58 percent respectively) than in developed countries (OECD emissions were predicted to grow at 10 percent, for example). As pointed out by O'Mara (2011), Europe, North America and the non-European Union former Soviet Union countries produced 46.3 percent of ruminant meat and milk energy and only 25.5 percent of enteric CH_4 emissions in 2005. In contrast, Asia, Africa and Latin America produced a similar amount (47.1 percent) of ruminant meat and milk energy, but a significantly large proportion (almost 69 percent) of enteric CH_4 emissions.

SCOPE AND APPROACH

In analysing the effects of various practices on non-CO_2 greenhouse gas CH_4 and N_2O emissions, the authors of this document did not account for the effect of these practices in the whole-farm or production cycle context. This task can only be accomplished through LCA analyses, which was beyond the scope of this report. We also did not account for economics of mitigation practices, which is again beyond the scope of this work. Various animal production systems will have different inputs and outputs (high-grain vs pasture in dairy and beef systems, for example) and these were not evaluated. Also, no efforts were made to recommend one production system over another. Markets, demand-supply relationships and consumer acceptance dictate the dominance of a production system in a particular geographical region or time. What is profitable for the farmer and acceptable for society today might not be so tomorrow.

An example of the above complex interactions is the US beef feedyard system. In this system, cattle are finished on 85 to 90 percent grain diets and one can argue that a system so heavily dependent on grains, that can be more efficiently used to produce meat and eggs from monogastric species or used directly for human consumption, is not sustainable in the long term. But the beef industry in the United States is market-driven and consumers are willing to pay the price to have grain-finished beef. On the other hand, United States grain growers have achieved exceptionally high yields and need a market for their product, which is provided by the livestock industry and, more recently, the biofuel industries. This match of demand and supply has been working well for the United States, but it will not likely be a model for other geographic and economic conditions.

In addition, some analyses based on LCA have shown that grain-fed beef has a lower environmental footprint than grass-fed beef systems (Crosson *et al.*, 2011; O'Mara, 2011) and that the largest GHG emissions in a beef production system (about 80 percent of the total) occur in the cow-calf phase, when cows and their calves are consuming predominantly forage-based diets (Beauchemin *et al.*, 2011). Analogous findings can be drawn for the dairy industry (Hagemann *et al.*, 2011). These analyses, however, do not always account for all inputs and outputs, and conclusions often depend on LCA assumptions.

According to some other estimates, inclusion of CO_2 emissions from all inputs and loss of soil organic matter (OM) from grain production or not accounting for C sequestration by grasslands, for example, may significantly change total CO_2-eq GHG emissions and account for the variability in results reported by LCA analyses from dairy production systems (Gill *et al.*, 2010; Martin *et al.*, 2010a; Doreau *et al.*, 2011a; Waghorn and Hegarty, 2011).

Approach

More than 900 publications were selected and reviewed during the preparation of this document. Our goal was to summarize and critically evaluate available CH_4 and N_2O mitigation practices. Metrics for estimating mitigation potential should be standardized, which would facilitate comparison of data from studies using different analyses. The term "emission intensity" (Ei - CH_4/unit animal product) has been introduced for enteric CH_4 emission (Leslie *et al.*, 2008) and, being based on emissions per unit of product, reflects most accurately the effect of a given mitigation practice on the composite of enteric CH_4 emission, feed intake and animal productivity when compared with scaling per unit of feed intake.

This analysis focused on CH_4 and N_2O as the major non-CO_2 GHG from animal agriculture. Ammonia (NH_3) is not a GHG but has significant environmental implications and therefore the effects of mitigation practices on NH_3 emissions (predominantly from manure storage and land application) were considered. Being a major air and water pollutant, the environmental effects of NH_3 are not localized to the area in immediate proximity to the emission source. The average lifetime of atmospheric NH_3 aerosol has been estimated at three to four days and we have estimated, for example, that NH_3 emitted from dairy farms in central Pennsylvania's watersheds can reach the Chesapeake Bay on the east coast of the United States in less than 24 hours (see discussion in Hristov *et al.*, 2011a). Based on a nitrogen (N) mass balance approach, we estimated that more than 25 percent of the feed N input on a dairy cow operation could not be accounted for in milk and manure after 24 hours (mostly being lost as NH_3; losses from beef cattle feedlots are even greater, reaching 50 percent) (Hristov *et al*., 2011a). For a 100-cow dairy, fed a 17 percent-crude protein (CP) ration (standard for the United States dairy industry), this loss can be as high as 12 kg N/day, or about 4 400 kg/yr. This N can be deposited through dry or wet deposition and can contribute to N runoff and ground water pollution as well as N_2O emission from soil. Thus, NH_3 emissions must be considered in the context of whole-farm environmental sustainability.

Within an LCA, CO_2-equivalent (CO_2-eq) is used, which standardizes input and output units across the production system. A good example of the importance of using the right units for evaluating GHG mitigation potential was given by del Prado *et al.* (2010). From a simulation analysis of mitigation practices on UK dairy farms, these authors concluded that most methods that reduced GHG emissions per unit of milk did so through increasing whole-farm

N use efficiency, with the result that less area was required to grow forages to produce the same amount of milk. However, there were increased GHG emissions per unit of farm land.

Our analysis placed a particular emphasis on animal experimentation data. Data generated by rumen-simulation *in vitro* batch or continuous culture (CC) systems were deliberately excluded. *In vitro* systems are convenient for screening a large number of treatments, with sufficient replication, and in a short time, at a fraction of the cost of an animal study. Due to various factors inherent to all *in vitro* systems, however, fermentation end-products accumulate (batch culture systems) and the original microbial community may degenerate and protozoa usually disappear. Continuous culture systems have been designed to alleviate this problem and provide a stable environment for testing the effects of rumen modifiers. However, neither batch nor CC systems can answer the question of long-term adaptability of the ruminal ecosystem to a treatment.

There are numerous examples of large discrepancies between *in vivo* and CC results within the same experimental series[1]. A meta-analysis of CC studies (180 studies with more than 1 000 individual treatments) concluded that CC systems are generally characterized by lower acetate concentrations, extremely low counts or lack of ruminal protozoa, and lower OM and neutral-detergent fibre (NDF) digestibilities compared with *in vivo* digestion (Hristov *et al.*, 2012a). This analysis showed that variability was much greater for CC compared with *in vivo* data.

Modelling and LCA are important and useful tools for predicting effects of individual mitigation practices and interactions between practices. The analyses of Velthof *et al.* (2009) and del Prado *et al.* (2010), mentioned above, are just two examples of the opportunities offered by these approaches. The intention of the current analysis, however, was to be based on *in vivo* experimental data, so that the conclusions and recommendations drawn can in turn be used in modelling and LCA exercises. Thus, it was judged that, with a few exceptions, *in vitro* data and data from modelling efforts would not be used in developing this document.

Another important point is that mitigation practices, particularly those related to enteric CH_4, must be studied for persistency of the effect, i.e. beyond the several treatment weeks of Latin square or crossover design trials typically used in animal nutrition and that are also potentially subject to carry over effects among treatments (Titgemeyer, 1997). The rumen ecosystem can adapt to some bioactive compounds (saponins, for example) and perhaps not to others (Makkar and Becker, 1997; Wallace *et al.*, 2002). Unfortunately, although scientists are clearly aware of this issue, very few studies have examined the long-term effect of mitigation agents or practices. Thus, for most of the enteric CH_4 mitigation practices discussed in this document, data for persistency of the effect are critically needed.

A research process for evaluating the effects of phytogenic substances on ruminal fermentation and CH_4 production was recently proposed by Flachowsky and Lebzien (2012). According to these authors, the evaluation process should include: (1) botanical characterization of the plant(s) and their composition; (2) analytical characterization of the active phytogenic substance(s); (3) *in vitro* studies to test effects of substances on rumen fermentation and methanogenesis (i.e. screening); (4) *in vivo* studies (e.g. feed intake,

---

[1] See Devant *et al.* (2001); Dann *et al.* (2006); Sniffen *et al.* (2006); Carro *et al.* (2009); Molina-Alcaide *et al.* (2009); and Cantalapiedra-Hijar *et al.* (2011).

rumen fermentation, CH_4 emissions); and (5) long-term feeding studies with target animal species/categories (e.g. animal health and performance, quality and safety of food of animal origin, environmental impact, adaptation of microbes). The last two steps of this list are critical, clearly apply to all rumen modifiers, and should logically follow any *in vitro* CH_4 mitigation project.

Finally, a critical aspect of all mitigation practices that must be considered is their likelihood of adoption. Farmers are unlikely to adopt practices that (1) have no production (i.e. economic) benefit for their operation; or (2) are not mandatory and/or supported by governmental subsidies (anaerobic digesters in the United States, for example). An example of an economically feasible mitigation practice is the reduction of excess protein in the diet of ruminant and non-ruminant species, which can not only decrease manure NH_3 and N_2O emission but can result in feed cost savings and increased profit for the producer.

Mitigation practices

Comprehensive reviews on CH_4 and N_2O mitigation technologies and overall farm sustainability have already been published[2] and data from these reports have been extensively used in the preparation of this document. Our analysis focused primarily on mitigation practices for ruminant animals because GHG emissions from these species represent over 75 percent of the total CO_2-eq emissions from livestock (Steinfeld *et al.*, 2006). Mitigation practices for the following on-farm areas of a production system were evaluated:

1. Enteric fermentation
2. Manure and manure management
3. Animal husbandry

The vast majority of the studies covered in this document examined mitigation practices in isolation and rarely discussed potential interactions in the context of the whole production system. As stated earlier, the implications of various interactions among mitigation practices can be better understood through LCA analyses. As concluded by del Prado *et al.* (2010) from a simulation of UK dairy farms, "*the effectiveness of a combination of GHG mitigation practices cannot be assessed by simply adding the effectiveness of each method applied singly*". These authors estimated a 45 percent reduction in GHG emissions (per litre of fluid milk produced) when five to eight mitigation practices were applied simultaneously, compared to a 55-65 percent reduction when the mitigation potentials of each singularly applied practice were simply added. In this case, the discrepancy in predicted impact was due mainly to N_2O emission predictions, where as the discrepancy in CH_4 emission estimates was negligible. These and other outcomes depend on model inputs and assumptions, but also suggest more complex manure-soil-plant than animal-manure system interactions.

It is also important that assessments of mitigation practices take into account "pollution swapping", i.e. decreasing the emissions of one GHG while increasing another or causing an upstream or downstream increase in the emission of the same GHG. Pollution swapping can occur as a result of diet manipulations, for example, the reduction of dietary N to mitigate N_2O emissions from soil application of manure may increase enteric CH_4 emission due to increase carbohydrate intake (assuming carbohydrates replace protein in the diet). Pollution swapping can also occur with the implementation of manure mitigation practices, for example, the use of nitrification inhibitors to decrease N_2O emissions may increase ammonium accumulation and consequently, increase nitrate leaching and NH_3 volatilization.

---

[2] See Harris and Kolver (2001); Clemens and Ahlgrimm (2001); de Klein *et al.* (2001); Boadi *et al.* (2004); Clemens *et al.* (2006); Monteny *et al.* (2006); Kebreab *et al.* (2006); Beauchemin *et al.* (2007b; 2009a); Ellis *et al.* (2008); de Klein and Eckard (2008); Christie *et al.* (2008); Pollok (2008); Roy *et al.* (2009); Baudracco *et al.* (2010); Eckard *et al.* (2010); Martin *et al.* (2010a); Place and Mitloehner (2010); Sarnklong *et al.* (2010); Beauchemin *et al.* (2011); Cottle *et al.* (2011); Crosson *et al.* (2011); Hristov *et al.* (2011a); and Goel and Makkar (2012).

The accuracy and precision of measurement techniques is another important consideration when examining mitigation practices. For example, several publications have reviewed various aspects of measuring enteric CH_4, with particular emphasis on the sulphur hexafluoride (SF_6) technique[3]. The SF_6 tracer method has been criticized for producing larger variability than established techniques for measuring CH_4 production, such as respiration chambers. McGinn *et al.* (2006) and Clark (2010), for example, found relatively good agreement in group mean CH_4 emission measurements between SF_6 and the chamber methods, but variability was greater with the SF_6 technique (Clark, 2010). The correlation between emission values obtained from individual animals and repeatability in the estimated rates was also low for the SF_6 method (Clark, 2010; Pinares-Patiño *et al.*, 2010). Various factors, including permeation rate (Pinares-Patiño and Clark, 2008; Martin *et al.*, 2010b), retention of the tracer in the digestive tract (Lassey *et al.*, 2011), and different behaviour of tracer vs tracee gases (Pinares-Patiño *et al.*, 2010) may affect CH_4 emission measurements with the SF_6 technique. *In vitro* gas production systems have been modified to measure CH_4 (Pellikaan *et al.*, 2011a; Navarro-Villa *et al.*, 2011), but they suffer from the same disadvantages as all *in vitro* techniques (see previous discussion). Novel *in vivo* approaches have also been proposed, but their accuracy and precision have not been established (Storm *et al.*, 2012; Nelson *et al.*, 2012). Thus, when evaluating mitigation practices, it is important to examine critically the measurement methods used, particularly in relation to enteric CH_4 production.

Overall, care must be taken against unrealistic expectations of non-CO_2 GHG emission reductions from the livestock sector. In any production system, profitability is often the most important decision-making factor that will determine adoption of the various mitigation practices discussed in this document. Any practice that requires additional investment and is not compensated by an outside entity (for example, government) or has a chance of decreasing animal productivity or increasing production cost, is likely to be rejected by the livestock producer.

> *When assessing the mitigation potential of various practices, users must consider the combined effects of interactions among animal-manure-soil-crop processes related to whole-farm profitability, effectiveness in the field (vs experimental results) and the likely adoption rate.*

ENTERIC FERMENTATION

Introduction to stoichiometry of rumen carbohydrate fermentation

Methane and CO_2 are natural by-products of microbial fermentation of carbohydrates and, to a lesser extent, amino acids (AA) in the rumen and the hindgut of farm animals. Methane is produced in strictly anaerobic conditions by highly-specialized methanogenic prokaryotes, all of which are archaea. In ruminants, the vast majority of enteric CH_4 production occurs in the reticulo-rumen. Rectal emissions account for about 2 to 3 percent of the total CH_4 emissions in sheep or dairy cows, according to Murray *et al.* (1976) and Muñoz *et al.* (2012), respectively. Murray *et al.* (1976) estimated that of the 13 percent of total enteric CH_4 produced in the hindgut of sheep, only about 11 percent is excreted through the anus with the remaining 89 percent being excreted through the lungs.

---

[3] See Lassey *et al.* (2001); Lassey (2007); McGinn *et al.* (2006); Pinares-Patiño and Clark (2008); Williams *et al.* (2011); Lassey *et al.* (2011); and Storm *et al.* (2012).

NATIONAL DAIRY DEVELOPMENT BOARD, INDIA

photo 2
Enteric CH_4 measurement in a cow using SF_6 technique in an Indian village

Figure 3 represents a simplified schematic of the main pathways of carbohydrate fermentation and end-product formation in the rumen environment. The general stoichiometry of the reactions has been described by Van Soest (1994) as follows:

$$C_6H_{12}O_6 \text{ (glucose)} + NH_3 \qquad \text{microbes} + CH_4 + CO_2 + \text{VFA}$$

Thus, the main products of microbial fermentation of carbohydrates are volatile fatty acids (VFA), CH_4, and CO_2. Alcohols and lactate are also formed during these processes, but it is generally recognized that they are relatively unimportant in the rumen (except in cases when lactate accumulates causing rumen acidosis). As stated by Van Soest (1994), the basic problem in anaerobic metabolism is the storage of oxygen (i.e. as CO_2) and disposal of hydrogen (H_2) equivalents (i.e. as CH_4). Methane, formed from CO_2 directly or through formate, is the most important "2H" sink (the ultimate acceptor of reducing equivalents from $NADH+H^+$, FADH2, or reduced ferridoxin, commonly referred to as 2H because pairs of protons and electrons are donated and accepted in metabolic reactions) in the rumen:

$$HCOOH + 6H \qquad CH_4 + 2H_2O \text{ or } CO_2 + 8H \qquad CH_4 + 2H_2O$$

Although CH_4 can be produced from VFA and alternative sinks for H_2 do exist in other environments (acetogenesis, for example), these processes appear to be of little significance in the rumen (Russell and Wallace, 1997). As shown in Figure 3, the major VFA (acetate, propionate and butyrate) produce various amounts of H_2 with propionate being a 2H sink and thereby decreasing the overall amount of 2H available to reduce CO_2 to CH_4. Propionate can be formed by two different pathways, succinate and acrylate, involving different bacteria, with the succinate pathway considered of primary importance in the rumen (Russell and Wallace, 1997).

Recently, a new group of methylotrophic methanogens (the so-called rumen cluster-C) that does not require hydrogen as an energy source has been described and appears to play a role in CH_4 formation in ruminants (Poulsen *et al.*, 2012). The relative role of these archaea in CH_4 emissions has yet to be confirmed but this is an important development that may explain the lack of relationship between observed reduction in CH_4 production and abundance of traditional rumen hydrogenotrophic methanogens (see, for example, Karnati *et al.*, 2009; Tekippe *et al.*, 2011). However, the relative importance of the acrylate pathway in propionate formation may increase in high-concentrate diets. Valerate, a minor VFA resulting from carbohydrate metabolism, can also be a net sink for reducing equivalents (Russell and Wallace, 1997), but owing to its minor nature, this pathway only results in a slight decline in H_2 production. The other two minor VFA in the rumen, isobutyrate and isovalerate, originate from the metabolism of branched-chain AA (valine and leucine, respectively), resulting in formation of CO_2 and NH_3 (Van Soest, 1994).

As argued by Wolin (1960), a theoretical fermentation balance for a given molar distribution of fermentation acids can be developed. In this development, major assumptions include 1) that the only fermentation products are acetate, propionate, butyrate, CO_2 and CH_4; and 2) that all fermentation products are formed from plant carbohydrates with the monomer formula $C_6H_{12}O_6$ (glucose).

The oxidation state of the substrate (the number of oxygen atoms per molecule, minus half of the number of H atoms per molecule) has to be equal to that of the products. Thus (in the following equations, all fermentation products are expressed in moles):

$$2\ CO_2 - 2\ CH_4 + 0\ \text{acetate} - 1\ \text{propionate} - 2\ \text{butyrate} = 0\ \text{glucose}$$

As all CH_4 must arise at the expense of CO_2, which is a product of the formation of acetate and butyrate:

$$CH_4 + CO_2 = \text{acetate} + 2\ \text{butyrate}$$

After rearranging the above equations, the moles of CO_2 and CH_4 are:

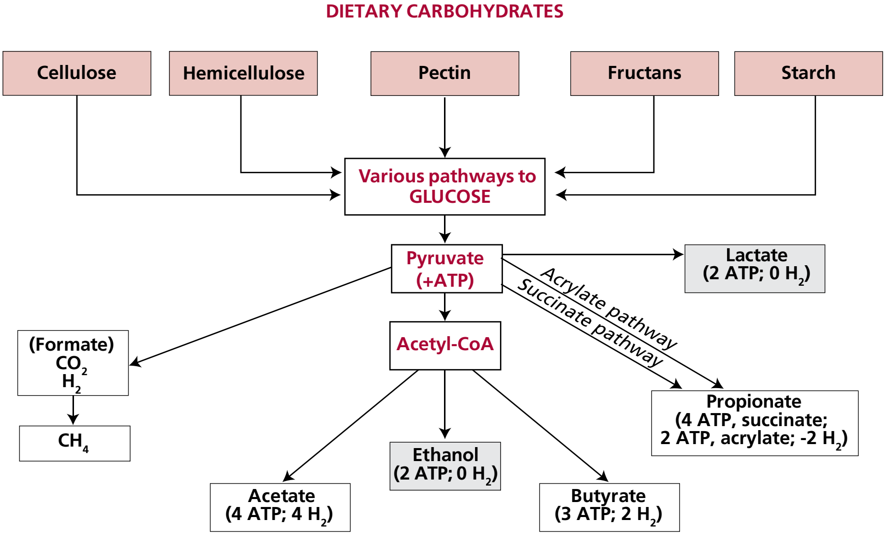
$$CO_2 = 0.5\ \text{acetate} + 0.25\ \text{propionate} + 1.5\ \text{butyrate}$$
$$CH_4 = \text{acetate} + 2\ \text{butyrate} - CO_2$$

Stoichiometrically, 1 mol of acetate may arise from the fermentation of 0.5 mol of glucose. Similarly, 1 mol of propionate may arise from 0.5 mol of glucose, whereas 1 mol of butyrate may arise from 1 mol of glucose. Hence the amount of glucose (moles) fermented is:

$$C_6H_{12}O_6 = 0.5\ \text{acetate} + 0.5\ \text{propionate} + \text{butyrate}$$

Assuming VFA molar proportions of 0.65 (acetate), 0.20 (propionate) and 0.15 (butyrate), based on the above equations 1 mol of total VFA arises from fermentation of 0.575 moles of glucose and is associated with 0.60 moles of CO_2 and 0.35 moles of CH_4. In other words, in this example 1 mol of glucose yields 0.61 moles of CH_4.

FIGURE 3
Carbohydrate metabolism in the rumen



Source: simplified from Van Soest, 1994 and Russell and Wallace, 1997.

It is important to point out that the above stoichiometric balance is valid only under two general assumptions (paraphrased from Van Soest, 1994 and based on Wolin, 1960): (1) that all excess H_2 appears as CH_4, which excludes alternative sinks coming naturally with the feed or added to the diet for mitigation purposes, and that no H_2 accumulates and is expired; and (2) that microbial growth, which may provide an alternative sink for H_2 in microbial protein and lipids, is not considered.

Janssen (2010) estimated that the amount of CH_4 formed from fermentation of glucose in the rumen can vary from 0 (0.67 acetate + 1.33 propionate; no net H_2 production) to 1 (2 acetate + 4 H_2) mol CH_4/mol glucose. Janssen (2010) concluded that CH_4 production in the rumen depends on the amount of H_2 formed and thus on the relative activities of various microbial species involved in fermentation pathways responsible for H_2 production. According to this author, H_2 concentration in the rumen can influence which pathways are active, thus positioning H_2 as a central regulator of pathway selection in the rumen.

The Janssen (2010) model needs to be extended when using nitrates or other electron competitors. Since sulphates present potential issues with H_2S production (Uwituze *et al.*, 2011), nitrates are discussed as a more promising additive. In an experiment by van Zijderveld *et al.* (2011b), cows were put into respiration chambers to measure gas production in real time, after stepwise adapting cows to nitrates to prevent nitrite accumulation. The first measurement, one hour after feeding, already showed much greater H_2 production for cows fed nitrate than those fed urea. Production of H_2 stayed lower for the next hour and then started rising to mirror CH_4 production, which reached the same amount as those in cows fed urea within six to eight hours.

Wollinella succinogenes and other bacteria anaerobically respire nitrate using H_2 more thermodynamically favourably than methanogens (Morgavi *et al.*, 2010). Presumably these bacteria would consume aqueous-phase H_2 concentration ($[H_2](aq)$) in competition with methanogens to divert it away from methanogenesis until the nitrate is depleted. However, *W. succinogenes* apparently has a K_m (Michaelis-Menten constant) for H_2 that is two to four times higher than methanogens (Asanuma *et al.*, 1999). Thus, enough nitrate needs to be added to overcome the affinity disadvantage. The dissolved H_2 would still be removed, whether by methanogens or nitrate reducers, so presumably acetate production could be maintained even when methanogenesis is decreased. Looking at the thermodynamics of acetate versus propionate production or measuring H_2 accumulation (van Zijderveld *et al.*, 2011b) would therefore presumably not explain VFA stoichiometry as well as if $[H_2]$ (aq) had been measured. Because H_2 entry into fermentative microbes is limited unless dicarboxylic acids are added (Martin, 1998), propionate production does not offer direct competition for H_2 already in the liquid phase (Janssen, 2010). Van Zijderveld *et al.* (2011b) demonstrated that the additional energy lost in H_2 production for the nitrate diet was minor and represented only 3.6 percent of the observed CH_4 decrease. Overall, the Janssen (2010) model needs further development to represent the dynamics of H_2 and CH_4 production and utilization when electron acceptors such as nitrate are applied.

The enteric CH_4 mitigation dataset generated for this document was divided into the following categories: *Feed supplements* (inhibitors, electron receptors, ionophores, plant bioactive compounds, dietary lipids, exogenous enzymes, direct-fed microbials, defaunation, and manipulation of rumen archaea and bacteria) and *Feeds and feeding management* (effect of feed intake, concentrate inclusion, forage quality and management, feed processing, mixed rations and feeding frequency, precision feeding and feed analyses, and mitigation options for production systems based on low-quality feeds). A summary of enteric CH_4 mitigation practices is presented in Table A1 (see Appendix 2).

Feed supplements

Inhibitors

Research in this area has targeted chemical compounds with a specific inhibitory effect on rumen archaea. Among the most successful compounds tested *in vivo* were bromochloromethane (BCM), 2-bromo-ethane sulfonate (BES), chloroform and cyclodextrin. These CH_4 inhibitors statistically reduced CH_4 production by up to 50 percent *in vivo* (in sheep/ goat and cattle). Examples are BCM/BES (Mitsumori *et al.,*2011 and Immig *et al.,* 1996); chloroform (Knight *et al.,* 2011); cyclodextrin (Lila *et al.,* 2004).

Earlier, Johnson *et al.* (1972) fed steers BCM [at about 1.1 g/100 kg body weight (BW)/ day] and found no effect on feed intake, average daily gain (ADG) or digestibility (the design of the trial was a Latin square), but they reported a dramatic decrease in CH_4 concentration in rumen gas: from undetectable CH_4 three hours after treatment, to 50 percent inhibition at 15 hours and no inhibition at 24 hours. Sawyer *et al.* (1974) fed growing lambs 0, 1.5 and 3.0 mg BCM/kg BW/day for 105 days and found no effect of treatment on feed intake and growth rate. In a parallel trial with wethers, the authors reported an 85 percent decrease in CH_4 production and no effect of BCM on digestibility or molar VFA proportions in ruminal fluid.

More recent reports also indicated that BCM may be an effective CH_4 inhibitor *in vivo*. In a series of experiments with Brahman cross steers, Tomkins *et al.* (2009) observed an up to 93 percent decrease in CH_4 production with BCM fed at 0.3 g/100 kg BW. In a follow-up experiment, the same dose of BCM decreased CH_4 production by about 50 percent, even at day 90 of the trial. There were no differences due to treatment in ADG, feed intake, feed efficiency and carcass quality, but BCM residues in tissues were not elevated. Although BCM has been banned since 2002 due to its ozone-depleting effect, the authors pointed out that their results may trigger interest in other compounds having a mode of action that is similar to that of BCM.

Another more recent study with goats receiving 0.3 g BCM/100 kg BW for 10 weeks (Abecia *et al.*, 2012) reported a 33 percent reduction in CH_4 production per unit of dry matter intake (DMI) and increased molar proportion of rumen propionate by close to 40 percent. These authors observed a striking 36 percent increase in milk production with no statistical difference in DMI. While some studies have suggested adaptation of the rumen ecosystem to this class of compounds (for example, Johnson *et al.*,1972 and Immig *et al.*, 1996), the effect (of BCM) appeared to persist in the studies by Sawyer *et al.* (1974), Tomkins *et al.* (2009), and Abecia *et al.* (2012).

Recent data by Knight *et al.* (2011) showed an immediate and dramatic drop in rumen CH_4 production in dry cows treated with chloroform. The effect appeared to persist for up to 42 days, although CH_4 production gradually increased to about 62 percent of the pre-treatment levels by day 42, suggesting adaptation to chloroform by the rumen ecosystem.

In conclusion, CH_4 inhibitors – specifically BCM and chloroform – are effective CH_4 inhibitors. It is apparent that a banned compound, such as BCM, cannot be recommended as a CH_4 mitigating agent, but compounds with similar mode of action may be developed. The long-term effect of CH_4 inhibitors is uncertain and more data are needed to establish their overall production effects. In addition, public acceptance (due to perception and/or existing or future regulations, or because they are known carcinogens, e.g. chloroform) could be barriers to adoption. Nevertheless, research groups around the world are working on developing natural or synthetic compounds that directly inhibit rumen methanogenesis and breakthroughs in the near future are possible.

> *Our conclusion is that bromochloromethane might be an effective enteric CH_4 inhibitor but, as an ozone-depleting compound and due to its poor acceptability in many countries, it cannot be directly used as a CH_4 mitigating agent. There are no sufficient long-term in vivo data for any other compound from this category as a CH_4 mitigating agent.*

Electron receptors

This category of CH_4 mitigating agents has recently received renewed attention. Among these, fumarate, nitrates, sulphates and nitroethane (Gutierrez-Banuelos *et al.*, 2007; Brown *et al.*, 2011) have been studied the most. Leng (2008) provided a comprehensive review of the earlier literature on nitrates. More recent research with sheep (Sar *et al.*, 2004; Nolan *et al.*, 2010; van Zijderveld *et al.*, 2010) and cattle (van Zijderveld *et al.*, 2011a,b; Hulshof *et al.*, 2012) has shown promising results with nitrates decreasing enteric CH_4 production by up to 50 percent.

Potential issues with these compounds include adaptation of the ruminal ecosystem, which, with perhaps one exception where nitrate persistently decreased CH_4 production from lactating dairy cows during four successive 24-day periods (van Zijderveld *et al.*, 2011b), has not been studied in long-term animal experiments. Additional issues with nitrates include potential increase in NH_3 production and potential toxicity from intermediate products (nitrite). The toxicity issue has been addressed in detail by Leng (2008). This author concluded that nitrite production from nitrate in the rumen may be prevented by feeding management.

In his review, Leng (2008) also emphasized the critical importance of gradual adaptation of the animal to nitrate and that low-protein diets are the natural background for successful utilization of nitrates as a CH_4 mitigating tool. The rumen ecosystem clearly has to adapt to dietary nitrates and acquire the ability to reduce nitrates rapidly to NH_3. This is evident by the gradual and marked increase in nitrate reducing bacteria activity following introduction of nitrate in the diet and the presence of distinct microbial groups in nitrate-adapted animals (Allison and Reddy, 1984). Therefore, in the studies of Nolan *et al.* (2010), van Zijderveld *et al.* (2010; 2011a,b), and Hulshof *et al.* (2012), nitrate was gradually introduced in the diet to allow adaptation, and no health problems occurred.

Leng (2008) also pointed out that sulphur may interact with nitrate metabolism in the rumen and discussed the potential role of molybdenum and alternative ways of supplementing ruminant diets with nitrate (through licking blocks or replacing liquefied NH_3 and urea as straw treatment). Urea-molasses multinutrient blocks are designed to provide urea, mixtures of minerals, and in some cases slowly degradable protein to animals in rangeland conditions (Sansoucy *et al.*, 1988). If nitrates replace urea in such molasses blocks, access to the blocks should be limited so that nitrate intake does not poison the animal. Intake of feed additives through licking blocks or liquid supplements can be extremely variable and this variability has to be considered when including potentially toxic substances such as nitrates. Cockwill *et al.* (2000) showed, for example, that intake of protein-molasses blocks by beef cows on pasture was on average 445 g/day, but varied from 0 to 1,650 g/day (SEM[4] = 438 g/day).

It is important to recognize that the adaptability of the rumen ecosystem to reduce nitrate may be short-lived after nitrate withdrawal from the diet. Alaboudi and Jones (1985) demonstrated that nitrate reducing activities of ruminal fluid of sheep acclimatized to nitrate at 2.5 g/kg BW/day dropped to their initial levels within three weeks after the KNO_3 supplement was withdrawn. This may be a critical safety issue and may prevent application of this mitigation strategy by smallholders in developing countries where feed availability and diets constantly change.

Nitrate level in the basal diet has to also be considered when supplemental nitrate is fed. Leng (2008) summarized data from Faulkner and Hutjens (1989) showing that some forages can have nitrate levels as high as 2.6 (corn silage) to 2.9 percent (green-chop sudangrass). At 2 percent of dietary dry matter (DM) and, for example, 25 percent inclusion of corn silage in the diet of a dairy cow consuming 25 kg DM/day, nitrate from the silage may be as high as 125 g/day. Nitrate levels in forages and pasture depends on N fertilizer application rates. As shown by Lovett *et al.* (2004), for each 1 percent increase in CP (from 13 to 23 percent) in perennial ryegrass from N fertilization, nitrate in forage increased linearly

---

[4] SEM = standard error of the mean.

by 0.035 g/kg DM, which further emphasizes the importance of accounting for the nitrate supplied by the basal diet. These data indicate that: (1) ruminants are naturally exposed to nitrate through their feed (Leng, 2008) and (2) nitrate supplied by the basal diet must be considered when supplementing nitrate for CH_4 mitigation purposes.

Nitrous oxide production in the gut is negligible. Earlier studies reported only traces of N_2O in the rumen as a product of nitrate reduction (Kaspar and Tiedje, 1981). These authors reported that up to 0.3 percent of the N added as nitrite accumulated as N_2O, without being further reduced. Based on these *in vitro* studies, the authors concluded that rumen N_2O was a by-product of dissimilatory nitrite reduction to ammonium rather than a product of denitrification and that the latter process is absent from the rumen. Indeed, concentration of N_2O in the rumen headspace of lactating dairy cows was about $\times 10^3$ lower than that of CH_4 (Hristov *et al.*, 2010b; 2011b). One study reported average daily emission of N_2O from dry Holstein cows housed in flow-through type metabolic chambers at 10.0 mg N_2O-N (Kurihara *et al.*, 2009). Based on data from their experiments, these authors calculated daily and yearly N_2O emissions from cattle at 5.2 ± 4.15 mg and 2.64 ± 1.65 g N_2O-N/per animal, respectively. Whether dietary nitrate supplementation can affect enteric N_2O emission in any significant way is unclear and needs to be investigated.

Adding sulphate to the diet of sheep reduced CH_4 production, and when both nitrate and sulphate were added, the effects of both products on CH_4 production was additive (van Zijderveld *et al.*, 2010). The potential effects of supplemental sulphate on animal health are also unclear. High inclusion of distiller's grains in feedlot diets in the United States has triggered intensive research on the effect of high-sulphur diets (also in combination with high-sulphur drinking water) on the occurrence of sulphur-induced polioencephalomalacia (Gould, 2000; Cammack *et al.*, 2010; Schoonmaker and Beitz, 2012), caused by excessive production of H_2S in the rumen.

The mitigation potential of electron receptors, specifically nitrates, has to be further explored, particularly in low-protein diets, where the rumen bacteria may benefit from a non-protein N (NPN) source following an essential adaptation period. Such a strategy may be particularly attractive in developing countries where forages contain negligible nitrate and insufficient CP for maintaining animal production. It has to be noted that ruminal microbial synthesis is enhanced by peptide and AA N (Russell *et al.*, 1992) and excessive amounts of NPN in the diet may negatively impact production or merely displace blood urea-N transfer in some dietary situations. Low total dietary N in the basal diet may be an important condition for a successful nitrate application so that enteric CH_4 mitigation is not offset by increased N_2O emissions from soil application of manure or a potential increase in rumen N_2O formation. Some loss of supplemental nitrate with urine is expected (Takahashi *et al.*, 1998), but its effect on total urinary N losses is unclear. In one study, nitrate supplementation did not increase volatile N losses from manure (Van Zijderveld *et al.*, 2011b), although the control diet was supplemented with urea and urine and faeces were not separated.

Fumaric and malic acids have also been studied extensively as alternative H_2 sinks in the rumen[5]. Their mitigating potential has been questioned (Ungerfeld *et al.*, 2007) because it is generally lower than that of nitrates and results have been inconsistent. In a number

---

[5] See Bayaru *et al.,* (2001); Molano *et al.,* (2008); Foley *et al.,* (2009); and Van Zijderveld *et al.,* (2011c).

of experiments, fumarate addition did not significantly affect enteric CH_4 production[6]. In some cases, feed intake was decreased (Foley *et al.*, 2009), which would inevitably have a negative impact on animal productivity and Ei. In a short-term study with lactating dairy cows on high-digestibility pasture, Kolver and Aspin (2006) did not find any effect on feed intake, milk solids (fat and protein) output or enteric CH_4 production of a relatively high dose of fumarate (5 percent of dietary DM). Similarly, Molano *et al.* (2008) did not report any reduction in CH_4 emissions/kg DMI when up to 10 percent fumaric acid was added to the diet of sheep.

One study investigated the effect of 10 percent (dietary DM basis) fumarate in a free or rumen-protected (to avoid negative effect on rumen pH) form on CH_4 production in a relatively long-term (43 days) study with lambs (Wood *et al.*, 2009). Using the tunnel technique to measure CH_4, the authors reported a 76 percent decrease in enteric CH_4 production with the encapsulated product with no effect on feed intake or the overall ADG. Because this dramatic CH_4-mitigating effect could not be explained by fermentation stoichiometry (the reduction was 2–2.5 times higher than based on the theoretical stoichiometric maximum), the authors discussed a possible adaptation of the rumen microbial community. Data were quite variable such that a 20 percent difference (n = 4) in ADG between the two fumarate products was not statistically significant. With the exception of this study, the long-term effects of these compounds have not been established over a variety of feeding conditions. Encapsulated fumarate did not produce any effect on enteric CH_4 in grazing dairy heifers in an earlier study by McCourt *et al.* (2008). Being organic acids, fumarate and malate are considered safe to feed.

> *Overall, nitrates may be promising enteric CH_4 mitigation agents, particularly in low-protein diets that may benefit from NPN supplementation. When nitrates are used, it is critically important that the animals are properly adapted to avoid nitrite toxicity. More in vivo studies are needed to fully understand the impact of nitrate supplementation on whole-farm GHG emissions (animal, manure storage and manure-amended soil), animal production and animal health. Fumaric and malic acids may reduce CH_4 production when applied in large quantities, but most results indicate no mitigating effect. The long-term effects of these compounds have not been established and cost is likely to prohibit their applicability.*

Ionophores

Monensin has been the most studied ionophore and is routinely used in beef production and more recently in dairy cattle nutrition in North America. Ionophores are banned in the European Union even though there is no evidence of genes coding for their resistance as there are with other feed-administered antibiotics (Russell and Houlihan, 2003).

There have been a number of experiments with monensin as a rumen modifier in various production systems, where enteric CH_4 production was studied as a main objective either from a mitigation or from an energy loss perspective[7]. Although some studies reported a long-term mitigating effect of monensin on CH_4 production (Odongo *et al.*, 2007), overall,

---

[6] See McGinn *et al.* (2004); Beauchemin and McGinn (2006); Kolver and Aspin (2006); McCourt *et al.* (2008); and Van Zijderveld *et al.* (2011c).

[7] See Sauer *et al.* (1998); Van Vugt *et al.* (2005); Waghorn *et al.* (2008); and Grainger *et al.* (2010a).

the effect of the ionophore appears to be inconsistent. In a meta-analysis of 22 controlled studies, monensin (given at 32 mg/kg DM) reduced CH_4 emissions and CH_4 conversion rate (Ym[8]) in beef steers fed total mixed rations by 19 ± 4 g/animal per d ($P < 0.001$) and 0.33 ± 16% ($P = 0.047$), respectively (Appuhamy *et al.*, 2013). The corresponding reductions in dairy cows were 6 ± 3 g/animal per d ($P = 0.065$) and 0.23 ± 14% ($P = 0.095$) for monensin given at a dose of 21 mg/kg DM. Overall, the conclusion of this analysis was 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.

Meta-analyses have shown monensin to produce improvement in feed efficiency in feedlot cattle (by 7.5 percent; Goodrich *et al.*, 1984), growing cattle on pasture (by 15 percent; Potter *et al.*, 1986), and dairy cows (by 2.5 percent; Duffield *et al.*, 2008), which may lead to reduced enteric CH_4 Ei. Moreover, another meta-analysis has also shown a consistent decrease in acetate:propionate (Ac:Pr) ratio with monensin addition in high grain diets fed to beef cattle (Ellis *et al.*, 2012b), which may lead to a reduction in CH_4 emission per unit of feed.

> *Our conclusion is that ionophores, through their effect on feed efficiency and reduction in CH_4 per unit of feed, would likely have a moderate CH_4 mitigating effect in ruminants fed high grain or mixed grain-forage diets. The effect is dose-, feed intake-, and diet composition dependent. The effect is less consistent in ruminants that are mainly fed pasture.*

Plant bioactive compounds (PBAC)

This category includes a variety of plant secondary compounds, specifically tannins, saponins, and essential oils and their active ingredients.

Tannins and saponins have been extensively studied and show the most promise for mitigating potential within this category. Tannins as feed supplements or as tanniferous plants have often, but not always (Beauchemin *et al.*, 2007a), shown a potential for reducing enteric CH_4 emission by up to 20 percent[8]. Condensed (and hydrolyzable) tannins are widely distributed in browse and warm climate forages and are usually considered anti-nutritional, although they can have good potential to reduce intestinal nematode numbers and allow acceptable production in the presence of a parasite burden (Niezen *et al.*, 1995, 1998a,b; Terrill *et al.*, 1992).

Tannins will inevitably be anti-nutritional when dietary CP concentrations are limiting production because they reduce absorption of AA (Waghorn, 2008). Structure, molecular weight and concentration of condensed tannins affect the nutritive value of the diet, and it is important that benefits of reduced CH_4 yields do not overshadow any detrimental effects of tannins on digestion and production, as observed by Grainger *et al.* (2009a) with dairy cows on pasture supplemented with grain. In this latter study, CH_4 emission was reduced by up to 30 percent, but milk production of the cows was also reduced by about 10 percent.

There has been extensive research into polyphenolic compounds, especially condensed tannins, in temperate forages under the European Union-supported "Healthy hay" and Marie Curie Legume^{Plus} programmes (http://sainfoin.eu/), but yield of temperate and trop-

---

[8] See Woodward *et al.* (2001); Sliwinski *et al.* (2002); Waghorn *et al.* (2002); Zhou *et al.* (2011a); and Staerfl *et al.* (2012).

ical tanniferous legumes is usually less than that of corresponding grasses, and agronomic properties often restrict their use. Nevertheless, nutritional and animal health (anthelmintic, bloat safe) benefits of tannin ingestion coinciding with reductions in methanogenesis and especially N_2O emissions, and the absence of N requirements for plant growth (most are legumes) makes these plants attractive for environmentally sustainable ruminant production.

A recent report by Verdier *et al.* (2012) indicated successful expression of a key regulator of the production of proanthocyanidins (i.e. one form of condensed tannin), MtPAR (*Medicago truncatula* proanthocyanidin regulator), in alfalfa resulting in detectable levels of proanthocyanidin in shoots. This suggests a possible pathway to the production of condensed tannins in this popular forage legume.

A meta-analysis of *in vivo* experiments with tannins by Jayanegara *et al.* (2012) reported a relatively close relationship between dietary tannin concentration and CH_4 production per unit of digestible OM. These authors, however, reported a trend ($P = 0.08$) for decreased feed intake and a statistically significant decrease in digestibility, particularly CP, with increasing dietary tannin concentration (a 0.16 percent decrease per g/kg DM extra tannin in the diet) but also for NDF with a 0.11 percent decrease per g/kg DM extra tannin in the diet. Results from a meta-analysis of C3 vs C4 grasses and warm and cold climate legumes by Archimède *et al.* (2011) concluded that CH_4 production was lower for animals fed high tannin legumes compared with animals fed low tannin legumes (37.2 vs 52.2 L CH_4/kg digestible OM intake). In studies with good quality diets containing condensed tannin with low astringency (Waghorn, 2008), feed intake and animal performance have not been negatively affected.

Reduced digestibility of diets containing condensed tannin is almost universal (Waghorn, 2008; Patra, 2010) and is unavoidable if urinary N loss is reduced because the dietary N is diverted to faeces (reducing apparent CP and OM digestibilities). This is an important factor that must be considered when feeding supplemental tannins or tanniferous plants, but relationships with digestion are affected by the type of tannin and the composition of the diet. In addition, the C fraction of condensed tannin is excreted in the faeces (Terrill *et al.*, 1994), so high concentrations of indigestible tannin in diets further limit digestible OM available to the animal.

There is enough evidence that tannins decrease silage NPN[9], but it is unclear if this reduction can have any measurable effects on dietary protein utilization and animal productivity. In some cases, animal production has been increased with inclusion of large proportion of tanniferous plants in the diet, even though total tract N digestibility was decreased. Inclusion of 60 percent birdsfoot trefoil *(Lotus corniculatus*) silage containing from 8 to 16 g/kg condensed tannins in the diet of lactating dairy cows increased milk yield (by about 3 to 4.5 kg/day compared with the control alfalfa silage), even though DMI was similar to the control and digestibility of fibre and CP were decreased (Hymes-Fecht *et al.*, 2013). The authors claimed better protein utilization with the birdsfoot trefoil silages, but the alfalfa silage diet contained higher CP and dietary protein was likely not limiting in this study because all diets contained about 17 percent CP. Research from the same group (Broderick *et al.*, 2012) reported no statistically significant effect of low-, medium- or high-tannin birdsfoot

---

[9] See Albrecht and Muck (1991); Broderick and Albrecht (1997); Tabacco *et al.* (2006); and Colombini *et al.* (2009).


INTERNATIONAL LIVESTOCK RESEARCH INSTITUTE

photo 3
A Horro sheep flock in western Ethiopia

trefoil silage on milk production of dairy cows. Feed efficiency and energy-corrected milk (ECM) feed efficiency in this study were decreased by the birdsfoot trefoil silages compared with alfalfa silage.

Tanniferous forages can have beneficial effects on silage quality and ruminant productivity and health (improved protein supply, bloat safety and antiparasitic properties; Broderick, 1995; McMahon *et al.* 2000; Frutos *et al.*, 2004). Discussion of tanniferous forages as cattle feed must, however, involve the agronomic characteristics of these species. In the case of birdsfoot trefoil, DM yields will most likely be inferior compared with alfalfa.

Chapman *et al.* (2008) investigated alternative forages for wild ruminants in western Canada and concluded that alfalfa had higher plant height, DM yields and CP concentrations, resulting in CP yields nearly double that of the other forages tested, including birdsfoot trefoil. Alfalfa also showed superior over-winter persistence, while birdsfoot trefoil stands exhibited poor competitiveness in the year of establishment. Alfalfa is called the "Queen of forages" not by accident and can be rarely outperformed in yield trials by any other forage species. Yields of alfalfa were higher than any other forage, including red clover and birdsfoot trefoil in trials in Wisconsin[10], New York[11] and Pennsylvania[12] in the United States. Birdsfoot trefoil, however, may have an advantage over alfalfa on soils of marginal fertility and production capabilities, and its excellent grazing potential and bloat-free advantages make it suitable forage for grazing systems[13].

An intensive interdisciplinary project investigated plant management, feed palatability and the antiparasitic properties, particularly useful for organic farming, of tanniferous forage (Häring *et al.,* 2008). These authors reported that sainfoin (*Onobrychis viciifolia*), birdsfoot trefoil and chicory (*Cichorium intybus*) were suitable for cultivation under the given

---

[10] Source: http://www.uwex.edu/ces/forage; accessed on 7 July 2012.

[11] Source: http://plbrgen.cals.cornell.edu/cals/pbg/programs/dayepartmental/forage/foragetest.cfm; accessed on 7 July 2012.

[12] Source: http://pubs.cas.psu.edu/FreePubs/pdfs/uc068.pdf; accessed on 7 July 2012.

[13] Source: http://pubs.cas.psu.edu/freepubs/pdfs/uc087.pdf; accessed on 7 July 2012.

temperate and climatic conditions of the particular area in Switzerland where the study was conducted, while big trefoil (*Lotus pedunculatus*) was outdone by unsown species. Dry matter yields increased when the tanniferous species were grown in a mixture with meadow fescue (*Festuca pratensis*). In this case, however, the tannin concentrations of the mixtures were lower due to a dilution effect. The study reported that palatability of the tanniferous forages was comparable to that of a ryegrass/clover mixture when fed as hay or silage, with the palatability of *O. viciifolia* being superior to that of the ryegrass/clover mixture. The authors concluded that *O. viciifolia* was a promising forage plant species due to its suitability for cultivation, high tannin concentration, high palatability and its antiparasitic activity.

Interestingly, in some studies protein degradation of tanniferous forages (38 sainfoin accessions measured in a short-term inhibitor *in vitro* system) could not be explained by any of the tannin assays (Lorenz *et al.*, 2012), further emphasizing the need for accurate tannin assays (Makkar, 2003). Degradation of plant tannins during ensiling of the plant, although not supported by sufficient research (Theodoridou *et al.*, 2012), might represent another issue with tanniferous forages. Oliveira *et al.* (2009), for example, reported condensed tannin concentration in silage from a high-tannin sorghum hybrid to be about 17 percent of that in the original forage (1.0 vs 5.9 g/kg DM). A recent study by Zhang *et al.* (2012) reported that tannins in *Leucaena leucocephala* were rapidly degraded during ensiling to about 40 percent of the initial concentration within 30 days of ensiling. Similar results were reported for high-moisture sorghum grain (Torterolo *et al.*, 2012).

One characteristic of research involving effects of tannins on animal digestion and productivity is the variation in responses among studies. Some of the variation may be explained by the type, concentration and protein binding capacity of the tannins and concentration of dietary CP (Jayanegara *et al.*, 2009); other causes of inconsistencies include variable techniques to measure the tannin concentration (Makkar, 2003) and failure to distinguish between condensed and hydrolyzable tannins (Mueller-Harvey, 2006) and the level of intake expected or required for optimal production. Condensed tannins can reduce the rate of digestion (Makkar *et al.*, 1995), but this will have little effect on animals fed at the maintenance level of intake because the rumen can accommodate more feed; however, in a lactating animal, production can be reduced because of bulk fill limitations on feed intake (Grainger *et al.*, 2009a).

We are not aware of any comparisons of efficacy between tannin as a component of feed and a dietary supplement, but Waghorn and Jones (1989) demonstrated that condensed tannin from one plant bound with proteins in another and affected their digestion, and both plant and supplemented extracts seem efficacious. An important consideration may be the emissions cost of extracting tannins from plants (e.g. from *Accacia mearnsii*) for use as additives compared with that present in plants and use of the plants for enteric CH_4 mitigation. In pasture-based systems, producers will be mostly interested in the suitability of tanniferous forages for their production system. However, plants expressing condensed tannin in the foliage (e.g. *Lotus* spp.) are less productive in fertile situations than are comparable temperate species (Waghorn, 2008).

In monogastric species, feeds containing tannins can reduce nutrient, particularly N, digestibility. Legume seeds, such as peas and beans, contain antinutritional factors and usually have lower N digestibility than soybeans in monogastric species (Gatel, 1994). An example of the effect of tannin content in field beans (*Vicia faba* L.) on N and AA digestibility in piglets is the study by Jansman *et al.* (1993). These authors fed field beans (at 30 percent inclusion rate) with low (0.6 g/kg) vs high (1.2 to 1.6 g/kg) condensed tannin content. Small intestinal and total tract N digestibility was decreased with all high-tannin varieties as compared with a low-tannin variety. Digestibility of individual AA was also decreased by 8 to 18 percent-units. An even more drastic decrease in N digestibility was reported for young chicks fed two tannin varieties of faba beans (*Vicia faba*) compared with a tannin-free variety (83 vs 68 percent, respectively) (Lacassagne *et al.*, 1988). Thus, tannins, supplemented through the diet, are undesirable for monogastric species, particularly when low-protein diets are fed.

A recent extensive review of the effect of saponins and tannins on CH_4 production in ruminants examined mostly *in vivo* studies with both PBAC (Goel and Makkar, 2012). The authors concluded that the risk of impaired rumen function and animal productivity with tannins is greater than with saponins and, for decreasing enteric CH_4 production, the concentration range for tannins is narrower than for saponins. In some dietary situations, however, decreased protein degradability in the rumen, combined with a shift in protein digestion to the small intestine, may be beneficial even if there is a decreased supply of digestible ruminally-undegradable protein (RUP). Such a shift may also have the benefit of reducing urinary N losses (vs faecal N losses).

According to Goel and Makkar (2012), the antimethanogenic effect of tannins depends on the application rate and is positively related to the number of hydroxyl groups in their structure. Overall, these authors concluded that hydrolyzable tannins tend to act by directly inhibiting rumen methanogens, while the effect of condensed tannins on rumen CH_4 production is more through inhibition of fibre digestion. They also pointed out that more animal research is needed with these compounds to establish their antimethanogenic effect. Methods for quantification of hydrolyzable tannins have also now become available (Makkar, 2003). It should be noted that hydrolyzable tannins are hydrolyzed in the rumen and some hydrolyzable tannins could be toxic (Lowry *et al.*, 1996; McSweeney *et al.*, 2003).

As with other CH_4 mitigating agents, the long-term effects of tannins and saponins have not been established. In addition, as indicated by Goel and Makkar (2012), a substantial reduction in CH_4 emission with these compounds, particularly tannins, would be difficult without compromising animal production. The study by Grainger *et al.* (2009a) is a good example of how digestibility, feed intake and ultimately production (and milk fat and protein yields) may be negatively affected if tannins (condensed in this case) are overdosed. These authors treated dairy cows for up to five weeks with two levels of condensed tannins (163 and 326 g/day) and reported statistically significant decreases in absolute CH_4 production with the tannin treatments, but no effect when CH_4 production was expressed per unit of fat and protein-corrected milk.

A more recent study with goats reported that a diet containing 5.6 g/kg DM tannins (both hydrolyzable and condensed) reduced the Y_m factor from 7.9 (control) to 6.0 percent of GEI, but OM digestibility was reduced by 10 percent-units, and CP digestibility by 14 percent-units (Bhatta *et al.*, 2012); CP digestibility was also reduced when diets containing a lower tannin concentration (2.8 g/kg DM) were fed. The effect of tannins is conditional on their composition (Waghorn, 2008; Goel and Makkar, 2012). As reported by Pellikaan *et al.* (2011b), *in vitro* gas and CH_4 production depended on tannin characteristics, such as type (condensed vs ellagitannins vs gallotannins), solubility, *cis-trans* configuration and browning rate. In this study, valonea and myrobalan tannins were most effective at reducing CH_4 production, with only a minor impact on total gas production.

Of the nine studies with saponins summarized by Goel and Makkar (2012), six reported decreased CH_4, from about 6 to 27 percent (absolute production, or per unit of BW or DMI). In three of these studies, however, OM digestibility was decreased and in another three, digestibility was not reported. From this analysis, it appeared that there was no difference in the CH_4-mitigation effect between steroidal saponins (*Yucca schidigera*) and triterpenoid saponins (*Quillaja saponaria*); *Y. schidigera* and *Q. saponaria* have been studied the most as sources of saponins because of their commercial availability.

Studies from China have examined the CH_4-mitigation effect of tea saponins (triterpenoid; Wang *et al.*, 2012) on enteric CH_4 production and animal performance. Hu *et al.* (2006) fed goats 0, 3 and 6 g/day tea saponins and observed an increase in feed intake and a consequent increase in ADG with the 3 g/day dose. Wang *et al.* (2009) reported an approximately 15 percent decrease in CH_4 production by sheep fed 170 mg/day *Y. schidigera* extract. Mao *et al.* (2010) reported no effect of tea saponins (3 g/day) on ADG of lambs but a 28 percent decrease in CH_4 production. In another study from the same group, Zhou *et al.* (2011a) reported a 6 to 10 percent mitigating effect of tea saponins on CH_4 production in restricted-fed sheep. Another group, Sliwinski *et al.* (2002) reported no effect of saponins (*Y. schidigera* extract) at 2 and 30 mg/kg dietary DM on CH_4 production in lambs. *Yucca schidigera* or *Q. saponaria* fed to dairy cows at 10 g/day had also no effect on milk production, total-tract nutrient digestibility, rumen fermentation or CH_4 production in the study of Holtshausen *et al.* (2009). Similarly, 3 g yucca powder per kg diet DM fed to dairy cattle did not affect feed intake, milk production and composition, digestibility, energy balance or CH_4 production in the study of Van Zijderveld *et al.* (2011c). Overall, with perhaps the exception of some data for tea saponins that require further validation, there is not enough evidence of consistent (or long-term) effect of saponins on enteric CH_4 production or animal performance.

A large number of *in vitro* experiments have investigated the CH_4 mitigating potential of essential oils and their active ingredients (Calsamiglia *et al.*, 2008; Bodas *et al.*, 2008; Benchaar *et al.*, 2009). Unfortunately, very few have followed up the *in vitro* work with *in vivo* experiments. In most cases, these PBAC have not been successful as CH_4 mitigating agents (Beauchemin and McGinn, 2006; Benchaar *et al.*, 2007; Van Zijderveld *et al.*, 2011c). In their recent review on the topic, Benchaar and Greathead (2011) concluded that some essential oils (e.g. garlic and its derivatives, and cinnamon) reduce CH_4 production *in vitro*. These compounds, however, have not been studied extensively *in vivo*, and there is no evidence that they can be used successfully to inhibit rumen methanogenesis. In some cases, as with *Origanum vulgare* leaves, the effect on CH_4 mitigation was significant, and there was also a trend for increased milk production and feed efficiency in dairy cows (Tekippe *et al.*, 2011; Hristov *et al.*, 2013), but these results remain to be confirmed in long-term experiments.

In conclusion, hydrolysable and condensed tannins are plant bioactive components that may offer an opportunity to reduce enteric CH_4 production, although intake and animal production may be compromised. The agronomic characteristics of tanniferous forages must be considered *when they are discussed as a GHG mitigation option. Tea saponins seem to have potential, but more and long-term studies are required before they could be recommended for use. Most essential oils or their active ingredients do not reduce CH_4 production and, when CH_4 production was reduced in vivo, their long-tem effects were not established.*

Dietary lipids

There is a large body of evidence that lipids (vegetable oil or animal fat) suppress CH_4 production in the rumen. The effects of lipids on rumen archaea are not isolated from their overall suppressive effect on bacteria and protozoa. Several reviews have attempted to develop prediction factors for the effect of feed lipids on rumen CH_4. Eugene *et al.* (2008) reported a 9 percent reduction in enteric CH_4 production in dairy cows due to lipid supplementation of the diet, but this was accompanied by a 6.4 percent reduction in DMI, which resulted in no difference in CH_4 per unit of DMI. However, these authors also reported no effect on 4 percent fat-corrected milk (FCM) which, combined with the reduced DMI, resulted in a trend for increased feed efficiency with oil supplementation. Further, when calculated per unit of FCM, CH_4 production decreased with lipid supplementation (0.82 vs 0.75 MJ CH_4 energy/kg 4-percent FCM; $P = 0.04$, n = 25).

A more recent meta-analysis of 38 research papers reported a consistent decrease in DMI with all types of dietary fat examined (tallow, various calcium salts of FA, oilseeds, prilled fat), but milk production was increased (Rabiee *et al.*, 2012). This combination of decreased DMI and maintained or increased milk production (assuming no decrease in milk fat) results in increased feed efficiency and, consequently, decreased enteric CH_4 Ei.

The greater inhibitory effect of unsaturated vs saturated FA on rumen microbial activity reported by Palmquist and Jenkins (1980) and Nagaraja *et al.* (1997) does not appear to apply to CH_4 production in most studies, although a greater mitigating effect of polyunsaturated FA was observed in the analysis by Doreau *et al.* (2011a). Biohydrogenation of unsaturated FA can also serve as a H_2 sink, but it has been suggested that only 1 to 2 percent of the metabolic H_2 in the rumen is used for this purpose (Czerkawski and Clapperton, 1984).

Beauchemin *et al.* (2007b) compared animal fat (tallow) and sunflower oil (about 48 percent higher unsaturated FA concentration in the diet), both supplemented at 3.4 percent of dietary DM, and reported no effect on DM and NDF digestibilities, feed intake and ADG in cattle. Methane production was reduced by about 12 percent by both lipid sources and there was no effect of level of saturated FA. In another study from the same group (Beauchemin *et al.*, 2009b), inclusion of crushed oilseeds in the diet of lactating cows at 9 to 10 percent of dietary DM (6.7 to 7.3 percent crude fat) decreased CH_4 production per unit of FCM by about 15 percent. There appeared to be a slight advantage of the oilseed with higher concentration of 18:3 (flax) compared with 18:2, or monounsaturated FA (about a 10 percent difference in CH_4 production). Two of the treatments dramatically reduced DM digestibility (10 to 20 percent), but this did not seem to affect feed intake or animal productivity.

Van Zijderveld *et al.* (2011c) exchanged a rumen inert fat source (fractionated palm oil; mainly C16:0) isolipidically with extruded linseed (mainly C18:3) or with a mixture of C8:0 and C10:0 FA. They reported no effect on DMI, milk production, NDF digestibility or CH_4 production (expressed in g/day, g/kg DMI, g/kg milk or percentage of GEI) indicating that these different FA sources did not differ in their CH_4 mitigating effect.

Recent meta-analyses by Moate *et al.* (2011) and Grainger and Beauchemin (2011) found a consistent decrease in CH_4 production with fat supplementation. Moate *et al.* (2011) reported the following relationship between dietary fat and CH_4 production per unit of DMI:

$$CH_4\text{ (g/kg DM)} = \exp\,[3.15(\pm\ 0.052) - 0.0035\ (\pm\ 0.00061) \times \text{fat, g/kg DM}]$$

Grainger and Beauchemin (2011) analysed 27 studies and concluded that, within a practical feeding rate of less than 8 percent 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. Similarly, Sauvant *et al.* (2011) also found a negative relationship between CH_4 production and dietary fat concentration. These authors did not find any significant difference in the response among lipids (mostly vegetable oils with various concentrations of unsaturated FA, such as canola, coconut, linseed, soybean and sunflower) and did not report effects on animal production (or feed intake, although the CH_4 mitigation effect was estimated on a DMI basis).

The important question of persistence of the effect of lipids on CH_4 production has not been adequately addressed. In a study with dairy cows on pasture, Woodward *et al.* (2006) examined the effect of vegetable and fish oils on milk production and CH_4 emission in short- (14 days) and long-term (12 weeks) experiments. Lipids significantly decreased CH_4 production in the short-term study, but this effect was not observed after 11 weeks of feeding lipids in the long-term study. These authors concluded that lipids were not beneficial for milk production and emphasized the need for long-term studies when developing on-farm strategies for CH_4 mitigation.

Some studies do report long-term effects of dietary oil, but data are inconsistent. Holter *et al.* (1992) found a statistically-significant decrease in CH_4 production in a 16-week study with lactating dairy cows when the diet was supplemented with whole cottonseeds (4.1 vs 6.8 percent total dietary fat), but the effect seemed to disappear when CH_4 production was expressed per unit of DMI or milk production (a dramatic 5.6 kg/day drop in milk production with cottonseeds). Whole cottonseed, however, has been reported as an effective CH_4 mitigation feed in long-term studies by Grainger *et al.* (2008) after five and after 12 weeks (Grainger *et al.*, 2010b).

Grainger and Beauchemin (2011) examined six long-term studies (six to 36 weeks, mostly with dairy cows), including the study by Holter *et al.* (1992), and concluded that the effect of dietary fat on enteric CH_4 production does persist but also pointed out that the effect is not consistent among studies. Persistence of the mitigating effect of dietary oil was also observed in the study of Martin *et al.* (2011) with flaxseed in dairy cows, although it was not supported by another study from the same group with young bulls (Eugène *et al.*, 2011).

As indicated earlier, biohydrogenation of dietary FA *per se* is a minor competitor for reducing equivalents compared with methanogenesis (Jenkins *et al.*, 2008), but modelling of biohydrogenation and integrating results with methanogen activity might help predict dietary conditions when lipid compounds are effective without adding significant risk for milk fat depression.

Attempts to use microbe-derived FA in milk as predictors of methanogenesis to support these efforts still suffer from profound bias among derivation data sets (Mohammed *et al.*, 2011), limiting their usefulness for prediction to future conditions. Dijkstra *et al.* (2011a), however, showed that CH_4 production could be predicted with promising accuracy in various experiments when both milk FA and CH_4 production were determined using similar techniques and equipment. Perhaps future attempts to make these equations more robust across diverse conditions need to account for differences in diet, milk production, or stage of lactation. In early lactation, changing forage:concentrate or adding rumen-inert fat had little effect on milk FA composition (Weiss and Pinos-Rodriguez, 2009). However, in later lactation, both decreasing forage:concentrate and supplementing fat decreased the proportion of short-chain FA (decreasing de novo synthesis), which would increase the secretion of FA (including microbially derived ones) absorbed from the small intestine. The balance between uptake and synthesis of FA in the mammary gland probably also contributes to differences in odd and branched chain FA in milk used for prediction purposes (French *et al.*, 2012).

The Monod growth kinetics model of Janssen (2010) predicts that methanogens would adjust to a higher [H_2(aq)] to maintain population density with the feeding of lipids and decreasing ruminal pH (typically through feeding higher grain or less effective fibre diets). Presumably, these events would be additive, so lipids plus lower pH would potentially combine to thermodynamically stimulate propionate production and decrease methanogenesis. Combining lipids with higher concentrate, presumably through lower ruminal pH, has been suggested to decrease protozoal counts (Firkins, 1996) but, unfortunately, it is also expected to decrease lipolysis and inhibit the terminal step of biohydrogenation (Jenkins *et al.*, 2008). That review discussed protozoal lipids being highly enriched in polyunsaturated and trans-11 FA, and both polyunsaturated fats and biohydrogenation intermediates are removed from the ruminal biohydrogenation pool through growth and ruminal passage of protozoa. Thus, CH_4 mitigation strategies combining lipids in dietary situations that limit rumination or enhance ruminal acidity can both decrease methanogenesis and depress milk fat synthesis. Yet, if ruminal pH is not decreased too much because of lack of effective fibre, decreasing forage particle size might increase ruminal passage rate to increase the rate of lipids entering this biohydrogenation pool (Lewis *et al.*, 1999). Increased passage rate of methanogens adherent to particles or perhaps protozoa passing with the particulate phase could decrease H_2 production according to the Janssen (2010) model.

In some studies, lipids had a significant and negative impact on DMI (for example, Martin *et al.*, 2008), a factor that must be carefully considered. Another important factor to take into account with lipids is that the increasing potential for mitigating CH_4 tends to correspond with increased likelihood of depressing milk fat and/or protein concentration, potentially with enhanced responses when combining lipids with other strategies such as ionophores (Mathew *et al.*, 2011). Some fats such as coconut oil, for example, can severely depress feed intake, fibre digestibility and, consequently, milk production and cause milk fat depression in dairy cows (Hristov *et al.*, 2004, 2009, 2011b; Lee *et al.*, 2011a; Hollmann and Beede, 2012), although they may be still beneficial as CH_4 mitigating agents (Machmüler and Kreuzer, 1999; Machmüller, 2006; Hristov *et al.*, 2009). Even a blend of mostly saturated long-chain FA (C16:0, C18:0, and C18:1) was found to cause a significant drop in feed intake and milk production, and a marked decrease (from 3.10 to 2.51 percent; i.e. a clear indication of milk fat depression, although not statistically significant) in milk fat concentration (Hollmann and Beede, 2012). Lipids causing this kind of production effects cannot be recommended as mitigation agents.

Studies on the effect of supplemental lipids on animal productivity are inconsistent. A review by Chilliard and Ferlay (2004) concluded that in most studies, milk production of dairy cows was increased with lipid supplementation (although rapeseed oil appeared to be an exception). The fattening cattle review by Clinquart *et al.* (1995) suggested that digestibility is decreased with lipid supplementation, but ADG and feed conversion may be improved.

The dataset developed for the analysis reported in this document contained 31 studies, in which oil supplementation was the main effect, with 105 treatments. Average CH_4 production was 19.5 g/kg DMI (SD = 7.2). Treatments included various types of oil, pure FA (myristic, for example), and whole and processed oilseeds such as canola, sunflower, cottonseed, etc. On average and compared with the study control, CH_4 production per unit of DMI was reduced in 81 percent of the oil supplementation treatments; the average reduction was 20 percent (SD = 13.9), min = 2 and max = 65 percent (coconut oil fed to sheep at 7 percent of dietary DM; Machmüller and Kreuzer, 1999). Dry matter intake was reduced in 49 percent of the oil supplementation treatments with an average reduction of 5.6 percent (SD = 6.6), min = 0.1 and max = 26 percent. Treatments with lactating animals (all dairy cows) were 29, of which in 15 (52 percent) milk production was reduced by oil supplementation, on average, by 9 percent (SD = 5.2), min = 1 and max = 20 percent.

Based on these data, it can be concluded that inclusion of lipids in ruminant diets will likely produce a CH_4-mitigating effect, but it may also depress feed intake and consequently, animal productivity. Therefore, at least part of the mitigation effect reported in the dataset is a result of decreased intake of dietary carbohydrate, which is a consequence of decreased DMI as a result of lipids replacing carbohydrate in the diet. For example, few studies measuring methanogenesis have replaced lipids for starch while maintaining the same concentration of rumen-degradable starch (e.g. by steam-flaking vs coarse grinding) or done meta-analyses to separate the direct from the indirect effects of lipid supplementation.

The economics of including lipids must also be considered. Vegetable oil prices have continuously increased on the world market over the last decade (soybean oil increased from US$343/tonne in Jan 2002 to US$1 131/tonne in Jan 2012; http://www.indexmundi.com), and it is questionable that feeding edible lipids to animals for the purpose of reducing CH_4 emissions is economical now or in the future. Moreover, in many markets, the butterfat differential would discourage fat supplementation practices that increase the risk of milk fat depression.

Although supplementing animal diets with edible lipids for the sole purpose of reducing enteric CH_4 emissions is debatable, high-oil by-products from the biofuel industries [dry or wet distiller's grains (DDG or WDG, respectively) or dry or wet distiller's grains with solubles (DDGS or WDGS, respectively), and mechanically-extracted oilseed meals] can naturally serve as a CH_4 mitigating feed, if included in the diet for economic reasons. McGinn *et al.* (2009), for example, reported up to 24 percent less CH_4 emissions when DDG replaced barley grain in the backgrounding diet of beef cattle by supplementing an additional 3 percent lipid to the dietary DM.

The effects of distiller's grains on CH_4 production, however, are not consistent and to a large extent may depend on the rest of the diet. Hales *et al.* (2012a) fed from 0 to 45 percent WDGS (substituting steam-flaked corn) to Jersey steers and observed a linear increase in enteric CH_4 emission per unit of DMI (up to 64 percent increase with the highest inclusion rate), due primarily to increased NDF intake, although the ether extract content of the diet increased from 5.9 to 8.3 percent. These authors reported Y_m of 2.4 (0 percent WDGS) to 3.7 percent (45 percent WDGS).

High-oil by-product feeds may have the same suppressive effect on feed intake as free lipids, so caution must be exercised to prevent negative effects on animal production or milk fat depression in lactating cows (Schingoethe *et al.*, 2009). Hales *et al.* (2012a), for example, reported about 11 percent decrease in DMI with the highest WDGS inclusion rate compared with the control. As little as 12 to 13 percent inclusion of mechanically-extracted canola or rapeseed meals with various FA compositions (replacing traditional, solvent-extracted canola meal) depressed DM intake and consequently, milk production in high-producing dairy cows (Hristov *et al.*, 2011c). These feeds also contain higher total N (relatively less digestible than N from the original seeds) and phosphorus (P), which may present an environmental challenge due to high N and P content of manure and, consequently, greater NH_3 and N_2O emissions.

A new trend in the bioethanol industry is partial extraction of oil from distiller's grains. It is estimated that more than half of the bioethanol plants in the United States are currently extracting oil from DDGS, with more plants expected to implement this practice in the near future. The industry is adopting oil extraction because of the additional income, which pays relatively quickly for the initial capital investment. Taking out about one-third of the oil from DDGS will reduce the energy value of the product but is likely to also reduce the CH_4 mitigating effect, discussed above, of these by-products.

An issue with distiller's grains, as well as with other by-products like whole cottonseed, is the increased dietary N concentration and intake, leading to increased potential for urinary N excretion and NH_3 and N_2O emissions from stored manure and manure-amended soil (see *Dietary management and N_2O emissions from manure*).

Spiehs and Varel (2009), for example, reported linear increase in urinary N and total manure P excretion with increasing WDG inclusion (0 to 60 percent) in the diet of beef steers. Similarly, Hales *et al.* (2012b) reported that inclusion of 30 percent WDGS in the diet of feedlot cattle increased total N excretion by 18 percent but urinary N losses by 35 percent, while dietary N intake was 23 percent higher compared with the control (0 percent WDGS). Distiller's grains are also inherently variable in composition (Spiehs *et al.*, 2002) and particularly intestinal digestibility of RUP and specific AA limiting production in ruminants (Boucher *et al.*, 2009).

Biofuel by-products may be available now due to increased ethanol (or biodiesel) production as a result of national energy policies in many countries, but their availability for feeding livestock in the future is not certain. According to a report by Searchinger *et al.* (2008), when land-use changes are accounted for, corn-ethanol production nearly doubles GHG emissions over 30 years and increases GHG for 167 years, when compared with gasoline. Removal of subsidies and the increasing price of corn further threaten the financial survival of these industries and makes availability of DDG as animal feed even more uncertain in the future.

Biodiesel by-products may also provide high-oil feedstuffs for livestock feeding. Biodiesel is considered as an environmentally sustainable, biodegradable fuel with lower C emissions, fewer particulates in exhaust emissions and substantially decreased sulphur dioxide emissions compared with fossil fuels (Sharma *et al.*, 2008; He *et al.*, 2009). Biodiesel can be made from various feed stocks with relatively small capital investment. With high oil yield per acre, canola/rapeseed are the preferred feed stocks for biodiesel production. Mechanically-extracted canola/rapeseed meals can have very high residual oil content (up to 17 percent, DM basis) and as indicated earlier, may depress DMI and milk production in dairy cows (Hristov *et al.*, 2011c). The oil in these meals is usually high in mono-unsaturated FA and, if included at levels exceeding 6 to 7 percent total dietary fat, will likely impair rumen function.

Numerous plants have been investigated as feed stocks for biodiesel/biofuel production. Sharma *et al.* (2008) listed over 37 indigenous plant species of India containing 30 percent or more oil in their seed, fruit or nut and meeting United States and European biodiesel standards on the basis of their FA composition. Among these plants, *Azardirachta indica* (concentrations of oleic and linoleic acids in plant oil: 61.9 and 7.5 percent, respectively), *Pongamia pinnata* (49.4 and 19.0 percent), *Jatropa curcas* (40.8 and 32.1 percent), *Madhuca indica* (46.3 and 17.9 percent), and *Calophyllum inophyllum* (42.7 and 13.7 percent, respectively) have attracted the attention of researchers and biodiesel manufacturers in India as potential feed stocks (Sharma *et al.*, 2008). The potential of the meals from these plants as animal feed has not been fully explored but, due to their high oil content (also high in unsaturated FA), they may mitigate CH_4.

Some oils from oilseeds have been engine-tested, their physicochemical properties have been described, and their oil yields estimated (Razon, 2009). Some of these lipids contain unique FA, but their effects on ruminal fermentation have not been studied. Castor oil (*Ricinus communis*), for example, contains ricinoleic acid which gives the oil its exceptionally high lubricity, but there is little information on the effect of ricinoleic acid on rumen fermentation (Wallace *et al.*, 2007). If any of these plants is used for biodiesel production on a larger scale, the meals will be available for feeding livestock, and research of their effects on ruminal fermentation, CH_4 production and animal performance is warranted.

One oil plant that has high unsaturated FA content, camelina (*Camelina sativa*; linolenic acid, 20 to 40 percent; linoleic acid, 10 to 20 percent; oleic acid, 12 to 25 percent; eicosenoic acid, 13 to 21 percent; and erucic acid, 2 to 5 percent of the plant oil) has been investigated as ruminant feed, specifically with the objective of increasing omega-3 FA in milk (and meat) fat. Hurtaud and Peyraud (2007) fed camelina seeds or meal to lactating dairy cows and reported a trend for decreased DMI (the meal contained 13 percent ether extract), no significant effect on milk yield and severe milk fat depression. Not surprisingly, there was a significant drop in the Ac:Pr ratio after feeding (from 2.74 to 2.02, control and camelina meal, respectively). A more recent study with camelina oil or expeller meal (total FA content of the camelina meal diet was 3.6 percent, DM basis) did not report any effect on digestibility, milk production or milk composition (Halmemies-Beauchet-Filleau *et al.*, 2011). It is unclear how these meals may affect absolute and per unit of animal product enteric CH_4 production.

Some non-edible meals and cakes from edible oil seeds can contain toxic compounds with potential adverse effect on animal health and productivity (*Balanites aegyptica*, *Ter-*

minalia bellirica, *Putranjiva roxburghii*, *Perilla frutescens*, *Madhuca indica* and *Moringa oleifera;* Abbeddou and Makkar, 2012). *Balanites aegyptica* cake, for example, contains steroidal sapogenins and is considered unsuitable for feeding livestock. Other examples are *Madhuca indica* cake, containing sapoglucosides that are bitter and toxic to livestock, and *Putranjiva roxburghii* kernels, containing phenyl, isopropyl and sec-butyl isothiocyanates of glucosides (Abbeddou and Makkar, 2012).

Other by-product feeds from emerging biofuel industries, such as microalgae (the so-called third-generation biofuels[14]), may become available if these industries develop. Algae, yeast, bacteria and fungi have the ability to accumulate lipids under some special cultivation conditions (Li *et al.*, 2008) and may potentially become an important feedstock for the biodiesel industry in the future, thus providing a high-oil by-product for animal feeding (Pabbi and Dhar, 2011). According to some, algal biofuels appear to be environmentally more sustainable than the biofuel production from cereal grains and oilseeds, and factors such as development in biotechnology, high crude oil prices and placing a high C-footprint value on GHG emissions may result in algal biodiesel being competitive with other fuels (Kovacevic and Wesseler, 2010). Transgenic plants with higher oil content have also been investigated (Winichayakul *et al.*, 2008), but there are not sufficient data to evaluate any of these approaches as a CH_4 mitigation strategy.

There have been attempts to introduce high-oil corn silage for the dairy industry in the United States. However, while the benefit of high-oil corn hybrids is in the increased energy content due to oil, which has more than twice the GE value of carbohydrates, the overall increase in net energy for lactation appears to be minimal because the increased energy from oil is diluted by the relatively small proportion of the oil in the whole corn plant DM and the decrease in starch content.

A study by Atwell *et al.* (1988) examined the effect of high-oil corn grain, high-oil corn silage and a combination of the two on lactating dairy cow performance. There were no production benefits of the high-oil corn or corn silage and feed efficiency was in fact decreased due to increased intake on the high-oil corn diets. An inconsistent effect or lack of response to high-oil corn and corn silage was reported by LaCount *et al.* (1995) and Whitlock *et al.* (2003), but Weiss and Wyatt (2000) observed increased milk yield with high-oil corn silage (at similar DMI). In this latter study, however, milk protein content was lowered by the high-oil corn silage, an indication of depressed rumen function, which is typically reported for feeds with high content of unsaturated FA (corn oil is about 80 percent mono- and poly-unsaturated FA). With lack of production responses, lower yields and higher seed cost, high-oil corn is unlikely to be a feasible feedstuff for cattle or a source of unsaturated oil for GHG mitigation purposes.

> *Our conclusion is that lipids are effective in reducing enteric CH_4 emission, but the feasibility of this mitigation practice depends on its cost-effectiveness and potential effects on feed intake (negative), productivity (negative) and milk fat content in lactating animals (positive or negative). High-oil by-product feeds such as distiller's grains, and meals from the biodiesel industry can serve as cost-effective sources of lipids with potential CH_4 supressing effect.*

---

[14] The first generation refers to biofuels from starch and sugars, and the second generation refers to biofuels from cellulose and other non-edible plant materials.

> *Their mitigating potential, however, has not been well-established and in some cases CH_4 production may increase due to increased fibre intake. There are a large number of non-traditional oilseeds being investigated as biofuel feedstock that, if available, may be used as livestock feed and have a beneficial effect on animal productivity (through improvements in energy and protein supply), including a CH_4-mitigating effect, although data to support this concept are lacking.*

Exogenous enzymes

The use of exogenous enzymes (EXE) in ruminants has been intensively studied during the last 20 years, and Grainger and Beauchemin (2011) recently reviewed their potential application to reduce enteric CH_4 production in the rumen. There is no evidence of direct effect of these preparations on CH_4 production, but they appear to improve diet digestibility and animal production in some studies. The responses, however, are inconsistent and the factors affecting the responses are not clearly understood.

A review of EXE studies with dairy cows (25 studies published in refereed journals) indicated that, with few exceptions, EXE failed to produce the desired effects and expected improvements *in vivo*, based on their performance *in vitro* (A. N. Hristov, Pennsylvania State University, USA.; unpublished data). Specific EXE products resulted in significant increase in milk yield in one or two trials, but these preparations were not further tested to confirm their effectiveness. In several studies, milk production, total tract digestibility of OM, NDF, and sometimes CP, were increased by EXE supplementation. Some of the effects were dramatic and not biologically reasonable. A typical example of this latter category was a study by Titi (2003), which showed that a fibrolytic EXE applied at 150 g/tonne forage increased milk yield by about 8 kg/day, a dramatic 37 percent increase compared with the control. At the same time, treatment had no effect on milk components (no dilution effect) and no effect on DMI, which resulted in a corresponding 37 percent increase in feed efficiency with the EXE treatment. The graphical data published in this report showed a difference in milk production of about 7 kg/day in favour of the EXE product in the first week of the study, which could only be a result of: (1) an "immediate effect" of the EXE preparation (unlikely), or (2) significant differences in cow productivity before assigning treatments and failure to account for these differences by using an appropriate experimental design and statistical model.

A similar example is the report by Gado *et al.* (2009) in which a 23 percent increase in milk yield was observed for the EXE group. In this case, however, the production effect could be easily explained by greater DMI for the group. An increase in total tract nutrient digestibility and specifically NDF (a striking 40 percent) with the EXE treatment apparently had no consequences on cow productivity. Cows in this trial appeared to have had an N intake that accounted for more than 10 percent of total DMI, and retained 415 g N/day (control) [corrected for N in milk, given that Gado *et al.* (2009) reported N balance to be 486 g/day calculated as the difference between N intake and N excreted in faeces and urine].

Thus, variability among responses resulting from limited data, experimental errors or using inappropriate application methods limit the ability to assess potential effects of EXE on animal productivity, feed efficiency and CH_4 mitigation. Nevertheless, increased digestibility is the most likely explanation for production effects in trials in which DMI was not affected by EXE supplementation.

There has been an effort by some groups to develop "second generation" EXE, i.e. products developed specifically for use in ruminant diets (Selinger *et al.*, 1996). Recently, some EXE were shown to increase feed efficiency in dairy cows by 10 to 15 percent (Arriola *et al.*, 2011; Holtshausen *et al.*, 2011) when added to the silage or to the whole diet, with these results expected to result from improved fibre digestibility. Forages contain about 30 to 70 percent NDF, and NDF digestibility in the ruminant digestive tract is typically less than 65 percent for North American diets (with about 50 percent NDF degradability in the rumen), but can be considerably higher for some grasses and grass silage-based diets (Tas *et al.*, 2005; Huhtanen *et al.*, 2009a).

Although NDF digestibility can be high, NDF turnover rate is usually slow and dependent on relatively slow degradation rates, breakage into small particles by chewing to enhance microbial colonization and passage to the intestines. Dietary treatments (like EXE) that improve physical breakage could increase the rate and extent of fibre degradation and intakes, but few studies appear to have examined mechanisms by which EXE affect changes in animal productivity. Thus, there might be an opportunity to increase fibre digestion in ruminants, which would help improve feed efficiency of forage-based diets. Improved feed digestibility may decrease fermentable OM in (stored) manure, thus reducing overall CH_4 emissions from ruminant production systems. On the other hand, some EXE products may in fact increase CH_4 production. An EXE with endoglucanase and xylanase activities, for example, increased CH_4 production per unit of DMI or milk yield by about 10 to 11 percent in a study by Chung *et al.* (2012), which was attributed, by the authors, to increased ruminal digestion of feed (although no measure of improved digestibility were reported). In the latter study, the EXE product had no effect on DMI or milk yield, which contradicted results from an earlier study with the same product (Holtshausen *et al.*, 2011).

> *Although limited data indicate that exogenous enzymes may increase feed efficiency and thus indirectly reduce enteric CH_4 production, inconsistencies in the data mean that exogenous enzymes cannot be recommended as an effective mitigation practice.*

Direct-fed microbials

Direct-fed microbials (DFM) are commonly used as supplements in animal production. Probably the most common DFM used in ruminant nutrition are yeast-based products (YPs). A variety of commercially-available products fitting the description of YP exists, including: live yeast (highly concentrated live yeast), yeast culture (yeast cells with varying viability and the fermentation medium on which they were grown; Fonty and Chaucheyras-Durand, 2006), or yeast products (a general term representing both live yeast and yeast culture). This variability among YP is reflected in inconsistent animal responses to YP. Earlier analyses reported increased DMI and milk yield in dairy cows, no effect on rumen pH but decreased lactate concentration, and increased duodenal microbial protein and methionine flows (considered the first limiting AA in lactating dairy cows and other farm animals), suggesting enhanced microbial protein synthesis in the rumen (Erasmus *et al.*, 1992; Poppy *et al.*, 2012). Strains of *Aspergillus oryzae* and *Saccharomyces cerevisiae* have been the most commonly studied.

Proposed modes of action of YP in the rumen include oxygen scavenging and supply of growth factors, thus inducing more favourable conditions for the activity of ruminal bacteria, particularly those involved in fibre digestion (Newbold *et al.*, 1996; Fonty and Chaucheyras-Durand, 2006). More recent meta-analyses reported an overall positive effect of various YP on milk yield in dairy cows (Van Vuuren, 2003; Desnoyers *et al.*, 2009; Robinson and Erasmus, 2009). The Robinson and Erasmus (2009) review reported that *S. cerevisiae* YP increased milk yield by 3.6 percent on average (over the control). The same YP had no effect on feed intake or milk production and composition of high-producing dairy cows (Hristov *et al.*, 2010b), which only emphasizes the variability and conditional effects of these products.

Robinson and Erasmus (2009), for example, suggested the magnitude of the effect of YP on milk production decreased with increasing the milk yield of the control cows. The meta-analysis by Desnoyers *et al.* (2009; 157 experiments with lactating dairy cows) concluded that *S. cerevisiae*-based YP increased ruminal pH, increased total VFA and decreased lactate concentration, and increased OM digestibility, but had no effect on Ac:Pr ratio. Feed efficiency calculated based on published DMI and milk yield in this analysis did not seem to differ between control and YP. In the Hristov *et al.* (2010b) study, methanogen-specific DGGE (denaturing gradient gel electrophoresis) analysis of rumen methanogens did not reveal any YP-specific banding patterns and this result was supported by the lack of effect of YP on ruminal CH_4 production and overall ruminal fermentation (pH, protozoal counts, VFA). The YP, however, slightly decreased NH_3 and CH_4 emissions from manure measured in a steady-state gas emission system.

The notion of using YP to mitigate enteric CH_4 production has been discussed (Newbold and Rode, 2006) but, with the exception of some exciting and unconfirmed *in vitro* results (Chaucheyras *et al.*, 1995), convincing animal data to support this concept are lacking. Mwenya *et al.* (2004), for example, reported a 10 percent decrease in CH_4 production in sheep fed a 70 percent forage/30 percent concentrate diet supplemented with *Trichosporon sericeum* YP, but production of CH_4 per unit of DMI was similar to that of the control. A study by McGinn *et al.* (2004) reported no effect of commercial YP on CH_4 production in beef cattle. Thus, the potential for mitigating rumen CH_4 production with YP appears to be through increased production, feed efficiency and overall ruminal health.

Other DFM interventions of ruminal fermentation include inoculation with lactate-producing and lactate-utilizing bacteria to promote more desirable intestinal microflora and stabilize pH and promote rumen health, respectively. A meta-analysis by Krehbiel *et al.* (2003) reported a generally positive trend for improved health in young, growing dairy or beef cattle treated with various DFM (mainly based on *Lactobacillus* and *Streptococcus* and in some cases *Propionibacterium* spp.). This review also pointed to several studies with lactating dairy cows, but the research is limited.

Overall, feeding DFM to feedlot cattle resulted in a 2.5 to 5.0 percent increase in ADG and around a 2 percent improvement in feed efficiency, whereas the response in DMI was inconsistent (Krehbiel *et al.*, 2003). Several studies have reported a successful establishment of DFM products based on *Megasphaera elsdenii* (one of the most important lactate-utilizing species in the rumen) in sheep and cattle, but effects on ruminal pH and fermentation have been inconsistent (Klieve *et al.*, 2003; Henning *et al.*, 2010). A recent study with early lactation dairy cows inoculated with *M. elsdenii* claimed decreased Ac:Pr as a result of the inoculation (although this was not evident from the published data) and a statistically significant increase in feed efficiency compared with the control cows (Aikman *et al.*, 2011).

There have also been other attempts to inoculate the rumen with fungi (*Candida kefyr*) and lactic acid bacteria (*Lactococcus lactis*) along with nitrate supplementation to both control methanogenesis and possibly prevent nitrite formation, but no consistent animal data have been reported (Takahashi, 2011).

> *In conclusion, there is insufficient evidence of the direct enteric CH_4 mitigating effect of yeast and other direct-fed microbials. However, yeasts appear to stabilize pH and promote rumen function, especially in dairy cattle, resulting in small but relatively consistent responses in animal productivity and feed efficiency, which might moderately decrease CH_4 emission intensity.*

Defaunation

Association and cross-feeding between ruminal protozoa and archaea have been established (Vogels *et al.*, 1980; Lee *et al.*, 1987; Finlay *et al.*, 1994) and are the basis for suggesting defaunation as a CH_4 mitigation strategy (Newbold *et al.*, 1995; Boadi *et al.*, 2004; Hristov and Jouany, 2005). However, the response in CH_4 to partial or complete defaunation has been variable.

Morgavi *et al.* (2010) calculated an average decrease in CH_4 production of about 10 percent due to defaunation, but the data were extremely variable. Moreover, all responses were attributed to loss of protozoa without accounting for depressed ruminal fibre digestibility, which promotes acetate/CH_4 fermentation pathways and typically accompanies defaunation (Eugène *et al.*, 2004). Research from the same group with beef cattle reported no effect on rumen methanogen abundance despite a 65 percent difference in protozoal numbers between a high-forage and a high-starch, lipid-supplemented diet (Popova *et al.*, 2011). Similarly, a 96 percent-reduction in ruminal protozoa in dairy cows treated with lauric acid had no effect on the 16S ribosomal ribonucleic acid (rRNA) copy number of methanogenic archaea (quantitative polymerase chain reaction), and DGGE also indicated no difference in the archaeal population structure due to reduction in protozoal numbers (Hristov *et al.*, 2011b).

With such variability and uncertainty in the response (see Morgavi *et al.*, 2011), defaunation cannot be recommended as a CH_4 mitigation practice. In addition, apart from lauric acid and coconut oil (Sutton *et al.*, 1983; Machmüller and Kreuzer, 1999; Hristov *et al.*, 2004, 2009, 2011b) and some vegetable oils high in unsaturated fatty acids (FAs) such as linseed (Doreau and Ferlay, 1995), which can severely depress DMI in cattle, there has been no effective and, more importantly, practical defaunating agent tested rigorously *in vivo*.

Protozoa also play an important role in fibre and OM digestion in the rumen (Jouany *et al.*, 1988) and, although the response is not consistent, defaunation may have a negative impact on digestibility, animal production and milk fat test in lactating animals. A reduction in the population of protozoa-associated methanogens may trigger an increase in the population of bacteria- or rumen fluid-associated methanogens, which will counteract a potential reduction in CH_4 emission due to defaunation. Furthermore, it is difficult to maintain ruminants free from fauna, and there is always the possibility of refaunation.

> *Our conclusion is that, based on the current data, defaunation cannot be recommended as a CH_4 mitigation practice.*

Manipulation of rumen archaea and bacteria

Significant efforts have been devoted to suppressing archaea and/or promoting acetogenic bacteria in the rumen. Vaccines against rumen archaea are based on the concept of a continuous supply of antibodies to the rumen through saliva. Similar approaches with undesirable rumen bacteria, such as *Streptococcus bovis*, appear to have produced some positive results (Gill *et al.*, 2000; Shu *et al.*, 2001).

Vaccines against archaea have been successful *in vitro* (Wedlock *et al.*, 2010). A vaccine produced from an array of archaeal species had no effect on methanogen populations or CH_4 production in sheep (Wright *et al.*, 2004), although the animals had higher specific immunoglobulin G titres in plasma, saliva and ruminal fluid (Williams *et al.*, 2009). In the latter study, however, CH_4 outputs measured after the second and third vaccinations were about 20 percent and 18 percent higher, respectively, than those for the control, but the difference was not statistically significant. Follow up work using vaccines prepared from New Zealand and Australian methanogen strains proved unsuccessful in reducing CH_4 production in ewe lambs (Clark *et al.*, 2004).

New approaches have involved identification of genes encoding specific membrane-located proteins from *Methanobrevibacter ruminantium* (perhaps the most important rumen methanogen) and using purified proteins (produced in *Escherichia coli*) as antigens to vaccinate sheep (Buddle *et al.*, 2011). In another approach, antisera were generated in sheep against sub-cellular fractions from *M. ruminantium*, which reduced microbial growth and CH_4 production *in vitro* (Wedlock *et al.*, 2010). According to the authors, these approaches will provide a platform for selecting and screening appropriate candidates for vaccine formulation (Buddle *et al.*, 2011).

Sequencing the genome of *M. ruminantium* has opened new frontiers and opportunities for inhibition of rumen methanogens and the potential to mitigate ruminant CH_4 emissions (Leahy *et al.*, 2010). Ruminal bacteria capable of utilizing H_2 and CO_2 to produce acetate exist in the rumen (Joblin, 1999). Although these bacteria do not seem to be able to compete with methanogens for H_2 under normal conditions (Fievez *et al.*, 2001a), they may be competitive if H_2 concentrations increase as a result of suppressed CH_4 production (Le Van *et al.*, 1998). The model of Janssen (2010) demonstrates a dynamic interaction between H_2, passage rate, propionate production and the growth and activity of methanogens in the rumen. These interactions need to be acknowledged in the development of vaccines, and this is an exciting and fast-developing area of research that may produce effective CH_4 mitigation technologies in the near future (Wright and Klieve, 2011).

Recent research has suggested that interventions at early life of the animal can trigger differential microbial rumen colonisation and development, which may result in differential rumen activity. In a study by Abecia *et al.* (2011), kids from mothers treated with BCM had reduced CH_4 production compared with kids from untreated mothers (although animals were group-fed and individual DMI was not reported), introducing the possibility that responses to rumen modifiers may be influenced by the mother and remain programmed in the animal's adult life. This interesting concept may offer new opportunities for mitigating enteric CH_4 emission in ruminants, but needs to be further tested and verified. Another interesting approach, using anti-methanogen antibodies to suppress CH_4 production, was shown to be ineffective *in vitro* (Cook *et al.*, 2008).

> *At this point, none of the existing rumen manipulation technologies are ready for practical application, but vaccines could be applied to all ruminants, including those with little human contact, such as sheep and beef animals on pasture. It is important to appreciate that vaccines require the host to produce antibodies against some of their microflora that are part of a symbiotic relationship, enabling ruminant survival on a fibre-based diet. To be effective, the vaccines have to cover the entire methanogen community and not just individual species. The extent of reductions in methanogenesis may only be 5 to 10 percent, and persistence of the effect is unknown, but the potential for widespread application makes this an exciting opportunity for future mitigation of enteric* CH_4 *emissions.*

Feeds and feeding management

There is a clear relationship between feed OM digestibility, concentrate feed or starch intake, and the pattern of ruminal fermentation. As argued by Wolin (1960), the stoichiometry of ruminal fermentation dictates that more H_2, and consequently CH_4, will be produced on fermentation of fibre as compared with starch (in the latter case reducing equivalents are used for propionate synthesis). Noziere *et al.* (2010), for example, estimated that VFA molar proportions (acetate, propionate, butyrate) would average, respectively, 66, 17 and 14 mol/100 mol for NDF and 41, 44 and 12 mol/100 mol for starch. Indeed, a 72 vs 52 percent concentrate diet produced a 59 percent increase in ruminal propionate concentration and a 44 percent drop in Ac:Pr ratio in lactating dairy cows, accompanied by milk fat depression (3.20 vs 4.20, respectively; Agle *et al.*, 2010b).

In a meta-analysis, Bannink *et al.* (2008) showed that the fermentation of sugars and starch will shift rumen fermentation toward production of propionate when pH in the rumen decreases. Sauvant *et al.* (2011) proposed a quadratic relationship between Y_m and Ac:Pr in ruminal fluid $Y_m = -1.89 + 4.61 \times Ac{:}Pr - 0.59 \times Ac{:}Pr^2$; n = 23 experiments. These authors also derived several relationships among Ac:Pr and dietary DMI, concentrate inclusion and milk FA.

Thus, it is generally believed that higher inclusion of grain (or feeding forages with higher starch content, such as whole-crop cereal silages) in ruminant diets lowers enteric CH_4 production. Beauchemin *et al.* (2011) estimated that implementing extensive forage feeding for growing beef cattle would substantially increase GHG intensity (6.5 percent increase). Similarly, Pelletier *et al.* (2010) reported 30 percent higher total GHG emissions for pasture-finished cattle compared with cattle in a grain-based feedlot system.

Effect of feed intake

Feed intake is an important variable in predicting CH_4 emission. Johnson and Johnson (1995) stated that as feed intake increases, the Y_m factor decreases by about 1.6 percent-units per each level of intake above maintenance. However, these authors also noted that a strong relationship among diet digestibility, intake and CH_4 production could not be demonstrated. Their data (Figure 1 in Johnson and Johnson, 1995) suggest no relationship between dietary GE digestibility and the proportion of GEI lost as CH_4. Increasing intake increases fractional passage rate and decreases digestibility. The decrease in digestibility will depend on diet quality.

The NRC (2001) model, for example, assumes that the decline in digestibility (expressed as total digestible nutrients, TDN) with level of feeding is a function of diet digestibility at maintenance intake (TDN percent-unit decline = 0.18 × $\text{TDN}_{\text{at maintenance}}$ – 10.3). Sauvant and Giger-Reverdin (2009) concluded from their meta-analysis that OM digestibility decreases linearly with increasing feed intake (OM digestibility, percent = 76.0 – 2.75 × level of feed intake, percent of BW). Similarly, these authors reported a linear decrease in Y_m with increasing feed intake.

In a meta-analysis of data from studies in which dairy (n = 247) and beef (n = 75) cattle were fed grass silage-based diets, Yan *et al.* (2000) generated CH_4 prediction models based on digestible energy intake (DEI) that included silage acid detergent fibre (ADF) or DMI proportions and level of feed intake:

CH_4 energy (MJ/day) = DEI, MJ/day × (0.094 + 0.028 × $\text{silage}_{\text{ADFintake}}/\text{total}_{\text{ADFintake}}$) – 2.453 × (level of intake above maintenance)

CH_4 energy (MJ/day) = DEI, MJ/day × (0.096 + 0.035 × $\text{silage}_{\text{DMI}}/\text{total}_{\text{DMI}}$) – 2.298 × (level of intake above maintenance)

Hegarty *et al.* (2010) proposed the following relationships among feed intake, digestibility (55 to 85 percent), and CH_4 production for growing lambs on pasture: "(1) an increase in DMI is associated with a linear increase in ADG, with the rate of ADG being greater for feeds of greater digestibility; (2) increased DMI is associated with increased CH_4 production. For diets of low to moderate digestibility, such as those consumed in extensive grazing systems in Australia, the CH_4 released per unit additional intake is greater than when high intakes of high-digestibility feed are consumed; (3) CH_4 production per unit of metabolizable energy (ME) intake is lowest for diets with high-energy densities; (4) although an increase in the intake of any diet reduces the emissions intensity of growth (g CH_4 produced per kg ADG), emissions intensity at any given DMI is less for high-digestibility feeds than for low-digestibility feeds; and (5) small changes in energy intake result in small changes in CH_4 output, but in large changes in animal performance." For (5), the authors gave the following example: assuming that a 30-kg lamb consumed 900 g/day of forage, an increase in digestibility from 65 to 75 percent would increase ADG from 51 to 101 g/day but would increase CH_4 output by less than 1 g/day and almost halve emissions/unit ADG (i.e. Ei), provided the animal has genetic potential for enhanced productivity.

Despite the obvious relationships among digestibility, intake and enteric CH_4 production (absolute or per unit of DMI), the Y_m factor used by IPCC (2006a) is calculated on a GEI basis only. Ellis *et al.* (2010) evaluated nine empirical CH_4 prediction equations and observed the Y_m factor model to perform adequately, compared with other equations. However, these authors argued that because it is based simply on GEI, Y_m does not have the capacity to fully describe changes in composition of the diet and has limited use when estimating the impact of varying nutritional strategies on CH_4 emissions. For example, the IPCC Y_m model could not decipher between an increase in CH_4 caused by an increase in DMI and a change in CH_4 caused by an increase in the fat content of the diet, which would have differing effects on the resulting CH_4 emission but may not differ in GEI.

> *Thus, the validity of the Y_m approach is questionable, and perhaps it is time to begin expressing CH_4 energy loss on a DE basis (or per unit of animal product), which will better reflect forage quality and other mitigation practices, such as grain or fat inclusion in ruminant diets.*

One example of the potentially misleading information of CH_4 emission based on GEI is the study of Boadi and Wittenberg (2002). These authors fed low-, medium- and high-quality forage (with 38.5, 50.7 and 61.5 percent *in vitro* OM degradability) to dairy and beef cattle and reported no statistical differences among forages in CH_4 emissions when expressed on GEI or DMI bases (6 to 7 percent or 29 to 32 litre/kg). In contrast, there were drastically greater emissions with the lower quality forages when expressed on digestible OM intake basis (83, 64, and 48 litre/kg, respectively).

Similar disagreement between enteric CH_4 emissions expressed on a GEI or DEI basis was reported by Kennedy and Charmley (2012). These authors fed tropical grasses (n = 5) and legumes (n = 5) of varying quality to steers and measured enteric CH_4 in respiration chambers. The correlation between CH_4 production on GEI (average of 6.2 percent), and DEI (average of 11.8 percent) basis was poor, r = 23.

Because DM (and specifically digestible OM) intake is perhaps the most important determinant of CH_4 production in ruminants, the effect of feed and forage quality on intake is paramount. Regressing data for DMI vs CH_4 production from the enteric CH_4 database developed for the current analysis (n = 377), produced the following relationship (Figure 4) (SE in parentheses):

$$CH_4\text{, g/day} = 2.54\ (4.89) + 19.14\ (0.43) \times \text{DMI, kg/day}\ (R^2 = 0.86;\ P < 0.001)$$

The dataset used to develop this relationship included all control treatment means and treatments classified as feeds, with outliers removed based on an absolute studentized residual value > 2 (the PROC REG regression procedure of SAS; SAS Inst., Inc., Cary, NC, USA). This relationship can be used to predict baseline enteric CH_4 production in cattle and small ruminants, after being validated against an independent dataset in comparison with the current IPCC Y_m coefficient.

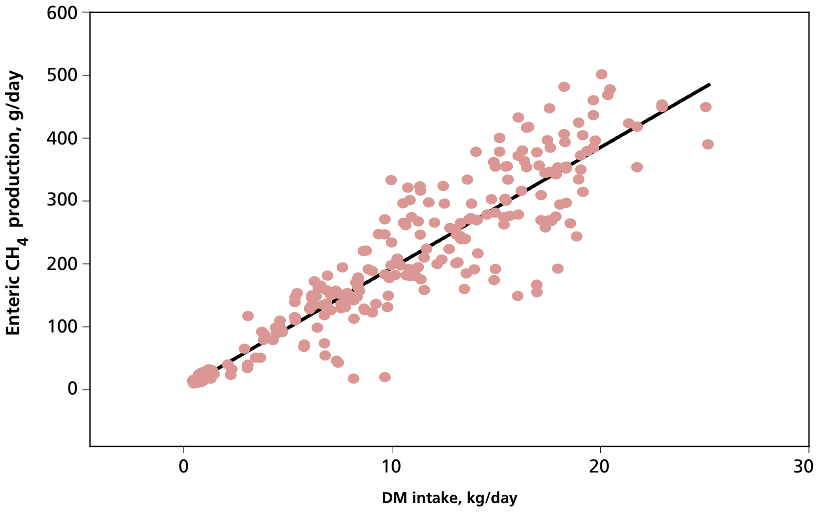
A similar coefficient for predicting CH_4 emissions per kg of DMI was reported for sheep (CH_4, kg/day = 0.0187 × DMI, kg/day) by Cottle *et al.* (2011) and for steers (CH_4, g/day = 19.6 × DMI, kg/day) in Australia by Kennedy and Charmley (2012).

It is worth mentioning that, if this equation is used, the prediction error would likely be greater with increasing DMI. The limitation is that the equation in Figure 4 is derived over a very large range of DMI, so the high R^2 suggests high precision; in contrast, shifting DMI in a more narrow range (e.g. a 10 percent increase from about 18 to 20 kg/day) would result in high variability, supporting the need for more research to explain this variation. In essence, this equation suffers from the same limitation as previously described for the fixed Y_m approach in IPCC, and expressing CH_4 production on a digestible DM basis may better represent the large variation between diets. Diet digestibility information, however, is not always available in the CH_4 mitigation literature.

Although CH_4 will increase with increasing DMI, the increase has to be interpreted in the context of a likely increased production of milk or meat which will decrease CH_4 Ei and

FIGURE 4

Relationship between dietary DM intake and enteric CH_4 production



may lead to an overall reduction in herd size in some production systems. Dry matter and DE intakes are unquestionably the most important factors driving animal production, and the equation in Figure 4 does not account for increased production and decreased enteric CH_4 on a product basis with increasing DMI. On the other hand, increased DMI usually decreases digestibility, which may increase excretion of fermentable OM with manure and thus, CH_4 or N_2O emissions depending on the type of manure handling system. As shown by Huhtanen *et al.* (2009a) in a meta-analysis of 92 trials (497 diets) with lactating dairy cows, intake had a negative effect on diet digestibility, although it was less than predicted by NRC (2001) and the Cornell Net Carbohydrate and Protein Model (Fox *et al.*, 2003). Huhtanen *et al.* (2009a) pointed out that diets which had high digestibility at maintenance exhibited greater depression in digestibility with increasing DMI. Another dietary factor that had a negative effect on NDF digestibility in that meta-analysis was the level of fat intake from concentrate feeds (see earlier discussion in *Dietary lipids*).

Concentrate inclusion

It is important to remember that dietary variables are not independent. Increasing or decreasing the concentration of one entity will decrease or increase concentration of another. For example, as discussed earlier, mitigation options aimed at reducing urinary N excretion may well result in elevated enteric CH_4 emission (Dijkstra *et al.*, 2011b). Decreasing dietary concentration of CP will result in increasing concentration of other nutrients (such as starch or NDF), and these changes may affect enteric and manure CH_4 and N_2O emissions. Thus, effects on GHG emissions as a result of changes in one nutrient have to be interpreted in the context of potential effects resulting from changes in other dietary constituents.

In a European study (Eugène *et al.*, 2011), addition of starch and lipid combination to the diet of feedlot bulls reduced GHG emissions per unit of feed intake and BW gain. In another study by the same group, higher grain inclusion in the diet of Blond d'Aquitaine bulls (70 vs 21 to 41 percent grain; the type of forages also differed) resulted in a dramatic increase in Y_m, from 3.2 to 6.9 percent, respectively (Doreau *et al.*, 2011b). The authors concluded that total CH_4 emissions (enteric and manure) were lowest for the high-grain diet, but N_2O and CO_2 emissions were greatest. Total GHG emissions were least for the high-grain diet (when C sequestration by grasslands was not taken into account).

The literature, however, is not consistent on this matter. Some studies have not reported a decrease in CH_4 production (absolute or per unit of feed DM intake) by increasing the proportion of concentrate feeds (for example, Beauchemin and McGinn, 2006; Popova *et al.*, 2011). In some cases, the opposite effect was observed, i.e. enteric CH_4 production increased (per unit of DM intake) with increasing concentrate inclusion in the diet (Islam *et al.*, 2000; McGinn *et al.*, 2006).

In general, concentrate will have a higher amount of fermentable OM (per unit feed) than roughage, which helps to explain an increased in CH_4 production. In a meta-analysis of 87 experiments with 260 treatments on growing and lactating cattle, sheep and goats, Sauvant and Giger-Reverdin (2009) found that CH_4 energy loss, as a proportion of GEI, was related to the concentrate proportion in the diet and level of intake (LI, as percent of BW):

$$Y_m = 10.8 - 2.99 \times LI + 0.40 \times LI^2 + 7.23 \times CPr - 8.71 \times CPr^2 - 0.98 \times CPr \times LI$$

where CPr is the proportion of concentrate in the diet.

According to the latter equation, at 50 percent concentrate in the diet, Y_m will be 9.2, 6.9, 5.4 and 4.7 percent of GEI for intake levels of 1, 2, 3 and 4 percent of BW. At 70 percent concentrate, Y_m would be 8.3, 5.8, 4.2 and 3.3 percent, respectively (Figure 5).

Some of the highest and lowest Y_m values estimated using the equation of Sauvant and Giger-Reverdin (2009) appear inconsistent with general findings on the level of CH_4 production; Y_m values as high as 9 percent or as low as 3 percent are unlikely to be encountered under standard feeding practices. Extrapolation of such empirical equations yields non-physiological levels of production, and intrapolation has to be performed with great care.

Ellis *et al.* (2010) evaluated nine CH_4 prediction equations that are currently being used in whole farm GHG models. In their analysis, equations that attempt to represent important aspects of diet composition performed better than more generalized equations. The Sauvant and Giger-Reverdin (2009) equation is an empirical prediction of CH_4, that does not include elements of the chemical composition of the diet as predictors. The important implication of the Sauvant and Giger-Reverdin (2009) analysis is that small and moderate variation in dietary concentrate proportion is unlikely to affect enteric CH_4 emission. As shown in Figure 5, marked improvements in Y_m can be expected beyond 35 to 40 percent inclusion of grain in the diet, but this will also depend on the level of feed intake. Increasing concentrate proportion in the diet from 0 to about 30 to 35 percent may actually increase Y_m. It should be noted that generally concentrate provides more digestible nutrients (per unit feed) than roughage. Hence CH_4 expressed per unit product is likely to decrease.

A meta-analysis using a mixed model regression analysis with a random study effect and data from 51 respiration chamber studies, including a total of 298 diets, was conducted by Ramin and Huhtanen (2013) to develop models for predicting CH_4 production from dietary and animal variables for dairy cow diets (< 75 percent of concentrates on DM basis). Only variables that were available or predictable when the diets were fed were considered. The best-fit equation for predicting the Y_m factor was (SE in parentheses):

CH_4-GE (kJ/MJ) = 1.5 (13.7) – 0.70 (0.072) × DMIBW + 0.073 (0.0134) × OMD_m – 0.13 (0.02) × EE) + 0.048 (0.0099) × NDF + 0.045 (0.0096) × NFC (adjusted root mean square error, RMSE, 3.18 kJ/MJ; CV = 5.54 percent)

where:
DMIBW is DMI/BW (g/kg),
OMD_m is OM digestibility at maintenance level of intake (g/kg), and
EE, NDF and NFC are concentrations (g/kg DM) of ether extract, NDF and non-fibre carbohydrates, respectively.

The best-fit equation for predicting the total CH_4 production was (SE in parentheses):

CH_4 (L/day) = – 136 (33.5) + 41.0 (3.11) × DMI – 0.67 (0.131) × DMI^2 + 0.25 (0.047) × OMD_m – 0.99 (0.116) × EE – 47.8 (21.56) × (NFC/NDF) (adjusted RMSE of 21.3 L/day),

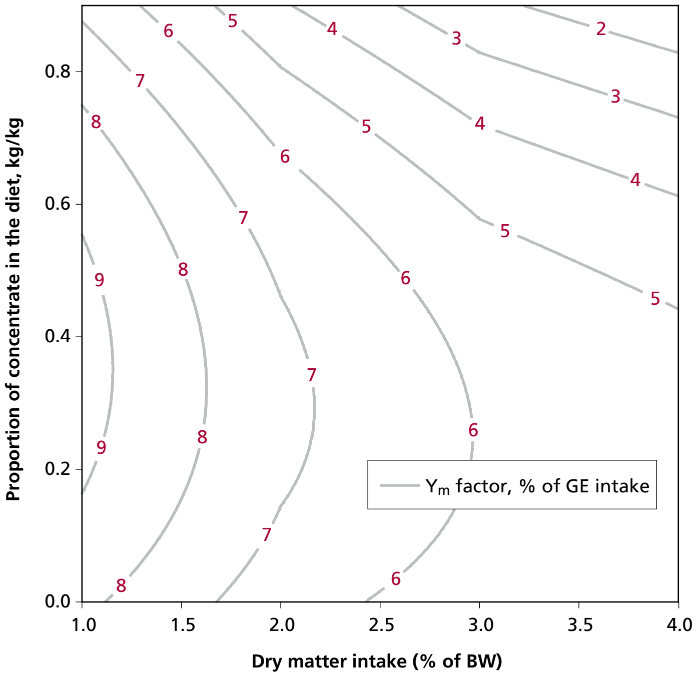
where:
DMI is in kg/day
OMD_m, EE, NDF, and NFC are as defined above.

The authors of that analysis concluded that feeding level and digestibility are the main determinants of Y_m and DMI is the main determinant of total CH_4 production. Concentration of EE had a negative effect on CH_4 production whereas dietary carbohydrate composition (NDF vs NFC) or proportion of concentrate had only marginal effects.

Feedlot cattle in North America are typically fed high grain diets (> 90 percent grain on a DM basis) to achieve maximum profit. In these systems, Y_m can be as low as 2 to 3 percent (Johnson and Johnson, 1995). Beauchemin *et al.* (2011) estimated that extended grain finishing of cattle from 170 to 210 days (i.e. shortened backgrounding period: 110 vs 40 days, respectively) would reduce GHG Ei of beef production by 2 percent, mainly due to lower enteric CH_4 emissions, reflecting shorter time to market and lower Y_m of grain- vs forage-based diets. There would also be less CH_4 emission from manure because its production would be reduced by 11.3 percent due to the greater digestibility of grain (Beauchemin *et al.*, 2011). However, the authors indicated that intensifying ruminant production by feeding less forage should be promoted as a GHG mitigation strategy only after careful assessment using LCA because these results may not be applicable to all beef production systems. In addition, increased feeding of grains to beef cattle may not be a viable long-term GHG mitigation strategy because it ignores the importance of ruminants

FIGURE 5

Effect of feed intake and proportion of concentrate in the diet on Y_m factor (CH_4 energy, % of GE intake)



Source: reconstructed based on Sauvant and Ginger-Reverdin, 2009.

in converting fibrous feeds into edible products, the shift in grain diversion to biofuels (and increased price), and the increasing priority of grains to feed a growing world human population.

Increasing the proportion of concentrate will lower enteric CH_4 emissions per unit of feed intake and animal product if production remains the same or is increased, which has been demonstrated in the classic works of Flatt *et al.* (1969) and Tyrrell and Moe (1972) and reinforced by others (Ferris *et al.*, 1999; Yan *et al.*, 2000).

In contrast with data from Sauvant and Giger-Reverdin (2009), some experiments with lactating dairy cows and beef cattle have shown linear decreases in enteric CH_4 emissions with increasing the proportion of concentrate in the diet (Aguerre *et al.*, 2011 and McGeough *et al.*, 2010). In the first case, the range of concentrate inclusion was from 32 to 53 percent of dietary DM, and in the second from 27 to 88 percent. In the Aguerre *et al.* (2011) study, DMI was not affected by concentrate inclusion (20 to 21 kg/day), but in the beef study, DMI decreased quadratically (by about 10 percent) with the higher concentrate inclusion

(McGeough *et al.*, 2010). In both cases, enteric CH_4 production decreased by about 0.28 g/kg DM, respectively, for every percent increase in the proportion of concentrate feed in the diet. For example, a reduction of about 2.8 g CH_4/kg DMI was observed for a 20 to 30 percent increase in the concentrate proportion of the diet. This reduction of 0.28 g/kg DM for a 1 percent increase in concentrate clearly contradicts results from the meta-analysis of Sauvant and Giger-Reverdin (2009). These authors predicted no change in Y_m at an LI of 3 percent of BW if concentrate increases from 20 to 30 percent (Y_m of 5.93 percent) whereas the relationship based on the Aguerre *et al.* (2011) and McGeough *et al.* (2010) studies predicted a decrease of 2.8 g CH_4/kg DMI (which on average corresponds with a decline in Y_m of 0.8 percent). There was no relationship between dietary concentrate and CH_4 emission in a study with sheep (Moss *et al.*, 1995). These authors included concentrate proportions from 0 to about 75 percent of dietary DM and did not observe any effect on CH_4 production at maintenance level of intake, but there was a quadratic decrease in CH_4 production with the higher plane of nutrition. Although rumen stoichiometry could not explain the change in CH_4 production, the authors argued that expressing CH_4 production relative to the efficiency of digestion, or the efficiency of animal production, might reveal the potential for reduction of CH_4 production by starch supplementation.

Such widely different predictions indicate that experimental results vary considerably and that in order to predict the consequences of increasing concentrate proportion, more information on chemical composition and degradation characteristics of the dietary feed ingredients is necessary.

Concentrate feeds due to higher concentration of DE than forages usually have a positive effect on the productivity of ruminants. Thus, increasing the proportion of concentrate in the diet should increase animal production and reduce enteric CH_4 Ei. The effect of concentrate feeds on milk production in dairy cows was demonstrated by Huhtanen and Hetta (2012) in a meta-analysis of 986 dietary treatments from change-over and continuous trial designs. These authors reported a highly significant and positive relationship between dietary concentrate intake and production of milk, ECM, milk fat and milk protein, irrespective of trial design.

A good example of the combined effect of concentrate supplementation and forage quality (i.e. forage digestibility expressed as maturity) is a recent study by Randby *et al.* (2012). In addition to no concentrate, these authors investigated the effect of three grass silage maturities (16.6, 14.5, and 11.3 percent CP and 47.7, 53.3, and 60.1 percent NDF; silage harvested at very early, early, and normal maturity) and three levels of concentrate supplementation on milk production of dairy cows. Concentrate supplementation reached up to 50 to 60 percent of DMI. Silage intake decreased with increasing grass maturity and total DMI increased with increasing concentrate supplementation. Energy-corrected milk yield decreased with increasing grass silage maturity and increased with increasing concentrate supplementation, most significantly up to 30 percent concentrate inclusion with little gain in milk production above 30 percent. However, ECM feed efficiency tended to decrease with increasing concentrate inclusion in the diet and was not significantly affected by silage maturity. A recent meta-analysis of 102 studies with lactating dairy cows found that increasing dietary starch concentration (average of 27 percent, DM basis; SD = 6.1) increased milk yield (by 0.08 kg/day per percentage unit increase in dietary starch) but decreased milk fat content and ruminal and total tract NDF digestibility (Ferraretto *et al.*, 2013).

Increasing the concentrate proportion in the diet above certain levels will have a negative impact on fibre digestibility (Firkins, 1997; Agle *et al.*, 2010b), which, in addition to a potential loss of production, will result in increased concentration of fermentable OM in manure and likely increased CH_4 emissions from stored manure (Lee *et al.*, 2012a). A meta-analysis of 142 diets from 59 studies with lactating dairy cows concluded that increasing dietary concentrate (average around 40 percent of DM with min = 0 and max = 72 percent) increased diet OM digestibility at maintenance level of intake but, similar to the analysis by Ferraretto *et al*. (2013), linearly decreased NDF digestibility (Huhtanen *et al.*, 2009b). Thus, decreased enteric CH_4 production (per unit of DMI) due to increased inclusion of grain in the diet may be partially offset by increased manure CH_4 emission from manure. To what extent these two processes will take place is an area that needs to be investigated and included in prediction models.

Cattle can adapt to high-grain diets, with a typical example being the feedlot system in the United States and parts of Canada. There is, however, a significant risk in negatively affecting rumen and animal health and consequently, animal performance with high-concentrate diets. Acute ruminal acidosis can damage the ruminal and intestinal walls, decrease blood pH, cause dehydration (that can be fatal), and result in laminitis, polioencephalomalacia and liver abscesses (Owens *et al.*, 1998). Strategies to reduce the risk and impact of rumen acidosis with high-concentrate diets include: (1) using feed additives that buffer rumen pH or selectively inhibit lactate producing bacteria; (2) stimulating lactate utilizing bacteria or starch-engulfing protozoa; (3) using microbial inoculants preventing glucose or lactate accumulation or metabolizing lactate at lower pH; and (4) including higher amounts of forage and proper grain processing (Owens *et al.*, 1998; Martin, 1998; Schwartzkopf-Genswein *et al.*, 2003; González *et al.*, 2012).

Moreover, forage:concentrate ratio profoundly affects DEI which is the main source of variation in the net energy feeding systems, and DEI has long been related to the shift in voluntary intake restriction from gut fill to chemical factors (NRC, 2001). Therefore, as stated earlier, researchers should standardize and report results relative to DEI, not GEI, for improved feasibility in future reviews.

Specific commodity feeds may also have an impact on CH_4 emissions. In one study, barley-based diets produced more CH_4 than corn-based diets (Yurtseven and Ozturk, 2009). As discussed earlier (see *Dietary lipids*), feeds with high oil content are likely to suppress CH_4 production in the rumen. For example, due to their high oil content, whole cottonseed has been shown to have a CH_4 mitigating effect in sheep (Arieli, 1992). A meta-analysis of a large dataset of trials with sheep (535 individual observations obtained using a closed-circuit respiration chambers methodology) by the Rowett Institute (Aberdeen, Scotland) showed that individual feeds can vary significantly in their methanogenic effects (Giger-Reverdin and Sauvant, 2000). The analysis classified feeds into four categories based on their generating potential: (1) high-CH_4 producing feeds (CH_4 energy > 12 percent of GEI): peas and fababeans; (2) medium-CH_4 producing feeds (CH_4 energy = 10 to 12 percent of GEI): wheat, corn, barley, sorghum, sugar beet pulp, soyabean meal, potatoes; (3) low-CH_4 producing feeds (CH_4 energy = 5 to 9 percent of GEI): green gramineae, wheat offal, rutabaga, cauliflower, oats, maize silage, groundnut meal, grass silages, dry grasses, lucerne silage, straw and lucerne hay; and (4) very low-CH_4 producing feeds (CH_4 energy

< 4 percent of GEI): distillers grains. It was concluded that lignin was the best predictor of CH_4 losses, and a model including DEI and chemical parameters, such as ether extract (EE), starch (St), CP and NDF (expressed as g/kg DM), explained over 90 percent of the variation in CH_4 emission (Giger-Reverdin and Sauvant, 2000):

CH_4 energy/GEI = $-$ 10.5 + 0.192DEI/GEI $-$ 0.0567EE + 0.00651St + 0.00647CP + 0.0111NDF ($R^2 = 0.92$)

To investigate the relationships among dietary nutrients and enteric CH_4 production, the authors of the present document developed prediction equations and identified key animal and dietary characteristics that determine enteric CH_4 production in cattle. Data for this analysis consisted of indirect calorimetric records of lactating and non-lactating cows (for details see Moraes *et al.,* 2013).

Model development was conducted in a meta-analytical manner by treating study effect as random. A cross-classified random effect was also estimated because animals were used in multiple studies. The statistical models were implemented in WinBUGS, using a Bayesian framework in which minimally informative priors were assigned for all parameters. Due to the uncertainty of model structure, a trans-dimensional modelling technique was implemented through the use of a reversible jump Markov Chain Monte Carlo method selecting best covariates to be used in the CH_4 prediction equations. Diet characteristics (fibre fractions, CP, EE and lignin), animal information (BW, breed), GEI and year of the study were used as possible covariates that could be selected with equal probability.

The following equations were developed (CH_4, expressed as CH_4 GE Mcal/day; GEI, Mcal/day; NDF, percent NDF in the diet, DM basis; EE, percent ether extract in the diet, DM basis; BW, kg):

- **Lactating cows:** CH_4 (GE Mcal/day) = 0.37 (0.37) + 0.0392 (0.0015) GEI (Mcal/day) + 0.0189 (0.0077) NDF (percent) – 0.156 (0.034) EE (percent) + 0.0014 (0.0003) BW (kg)
- **Dry Cows:** CH_4 (GE Mcal/day) = 0.45 (0.13) + 0.0503 (0.0014) GEI (Mcal/day) – 0.0556 (0.015) EE (percent) + 0.0008 (0.0002) BW (kg)
- **Heifers and steers:** CH_4 (GE Mcal/day) = – 0.056 (0.122) + 0.0447 (0.0028) GEI (Mcal/day) + 0.0039 (0.0018) NDF (percent) – 0.033 (0.019) EE (percent) + 0.00141 (0.00014) BW (kg)

These equations may be useful for predicting changes in enteric CH_4 production in dairy cattle triggered by changes in diet ingredient composition, concentrate proportion and forage quality.

Although empirical equations may have limited applicability for inventory purposes, they have major limitations in predicting effects of mitigation strategies. A more detailed prediction based on characteristics of dietary ingredients will give better insight into mitigation options. For example, Ellis *et al.* (2010) concluded from a thorough analysis of various empirical prediction equations against independent data that the low prediction accuracy of CH_4 equations in whole farm models may introduce substantial error into inventories of GHG emissions at the farm level and lead to incorrect mitigation recommendations.

Mechanistic models that describe the mechanism of CH_4 production based on knowledge of degradation processes in the rumen and type of VFA formed give better predictions than empirical models (e.g. Alemu *et al.*, 2011) and might provide insight into possible mitigation options. Indeed, a mechanistic model is now used for GHG inventory purposes in the Netherlands as an IPCC Tier 3 alternative to the IPCC Tier 2 fixed Y_m approach to estimate CH_4 production of dairy cattle. Unlike the Tier 2 approach, the Tier 3 approach does show different behaviour in CH_4 production in the past two decades when compared with the Tier 2 method because the mechanistic model is capable of representing changes in CH_4 production that result from changes in diet composition that occurred over these two decades (Bannink *et al.,* 2011).

One has to keep in mind that, globally, most ruminants consume forages which are often grazed and vary from very good to very poor quality. In these situations, addition of grain or even level of intake may have little relevance to CH_4 emissions. In some studies from developing countries, 10 percent concentrate supplementation of a poor-quality forage diet (sorghum with about 9 percent CP and 31 to 32 percent crude fibre) increased ADG of cattle and buffalo (Khanum *et al.*, 2010). Although these authors reported 10 to 14 percent reduction in enteric CH_4 production, the results must be interpreted with caution because CH_4 production was not directly measured but estimated from VFA concentrations, which is a questionable approach (Robinson *et al.*, 2010). More studies with poor-quality forages are needed to elucidate the effect of concentrate supplementation and/or forage processing on enteric CH_4 emission.

> *Overall, the inclusion of concentrate feeds in the diet of ruminants will likely decrease enteric* CH_4 *emission intensity, particularly when inclusion is above 35 to 40 percent of DMI, but the effect will depend on inclusion level, production response, effects on fibre digestibility, rumen function, and milk fat content, plane of nutrition, type of grain and grain processing. Supplementation with small amounts of concentrate feeds will likely increase animal productivity and thus decrease GHG emission intensity, although absolute* CH_4 *emissions may not be reduced. In spite of these potential gains, concentrate supplementation cannot be a feasible substitute for high-quality forage for ruminants. In addition, in many parts of the world, this may not be an economically feasible and socially acceptable mitigation option. Several comprehensive meta-analyses have produced equations based on animal characteristics, feed intake and diet composition that may be useful in predicting the effect of concentrate feed supplementation on* CH_4 *emissions from dairy cattle.*

Forage quality and management

An important feed characteristic that can impact enteric CH_4 production is forage quality, *specifically its* digestibility. As noted by the classic work of Blaxter and Clapperton (1965), increased intake of poor-quality, less digestible feeds has little effect on CH_4 production when expressed on a DM intake basis. For feeds with higher digestibility, however, increased intake results in a depression in the amount of CH_4 produced per unit of feed consumed. Moreover, it decreases CH_4 produced per unit of product by diluting maintenance energy.

Forage quality, level of concentrate, diet digestibility and feed intake are interrelated and directly affect enteric CH_4 production in the rumen. Forages are the feed ingredients with the largest variability in composition and have the largest impact on diet digestibility. Factors, such as plant species, variety, maturity at harvest and preservation can all affect forage quality and digestibility.

Lignin is the key element that limits forage cell-wall digestibility; as the plant matures, phenolic acids and lignin are deposited and cross-linkage of lignin and cell-wall polysaccharides are formed by ferulic acid bridges limiting polysaccharide digestibility by the animal (Jung and Allen, 1995). Concentration of NDF (and ADF) also increases with increasing maturity of the plant as its digestibility decreases. Dietary fibre concentration is one of the factors determining feed intake in ruminants.

Feed intake is a critical factor for improving animal productivity, feed efficiency and GHG emissions (both CH_4 and N_2O). Mertens (1994) and Allen (2000) have discussed in detail feed intake regulation in ruminants. There are a number of physical (palatability and fill limitation) and physiological (rumen propionate production) factors that control feed intake. According to Mertens (1994), feed intake is affected by management (animal handling, feed accessibility, frequency of feeding, method of feed presentation), feed (feed palatability, feed physical properties, such as processing, chemical composition, nutrient availability, plant species, etc.), and animal (capacity to ingest food, appetite and energy demand) factors. Dietary NDF concentration is among the most important regulators of feed intake through the so-called fill limitation mechanism (Mertens, 1994). Thus, NDF content of the diet and NDF intake are critical for achieving optimum animal productivity and minimizing GHG emissions.

Forages vary significantly in their NDF content and NDF digestibility. Grasses, for example, have higher cell-wall (NDF) content and NDF is generally more digestible than legumes. As pointed out by Jung and Allen (1995), plant improvement for grasses should target a reduction in cell-wall concentration, while improved cell-wall digestibility should be the selection target for legume forage species. Within grasses, C3 (“cool season”) grasses are more digestible than C4 (“warm season”) grasses (Reid *et al.*, 1988), with the latter having higher concentrations of lignin p-coumarate esters (Jung and Allen, 1995). However, forage composition must be considered within the context of the whole diet.

Broderick *et al.* (2002), for example, compared ryegrass silage vs alfalfa silage as part of total mixed ration (TMR) for lactating dairy cows. The diets were isonitrogenous and contained a similar amount of NDF, but the alfalfa silage diet had greater concentration of total and indigestible ADF. Feed intake was much higher with the alfalfa silage diet (about 50 percent higher; feeding was *ad libitum*), which resulted in 15 percent greater milk production but much lower feed efficiency (1.65 vs 2.15 kg/kg, respectively). Fibre digestibility was also considerably higher with the grass silage diet (about 50 percent higher). Thus, forage composition and digestibility must be considered as part of the whole diet, along with its effect on feed intake and animal production, all which can have an impact on GHG emissions from the rumen, manure or manure-amended soil.

The enteric CH_4 database compiled for the current analysis contained numerous references on effects of forage quality, pasture management and processing on CH_4 production in various species. The experimental treatments varied widely among studies, and comparison of different forages or supplementation strategies also included the confounding effects of digestibility on enteric CH_4 emissions. In general, enteric CH_4 reductions are

DAIRYNZ, G. WAGHORN

photo 4
Intensive grazing dairy production system in New Zealand

correlated with greater nutrient quality and digestibility, two attributes for which forage type and maturity might be indicators. Grazing management might be used as a potential mitigant through optimizing pasture maturity, allowing for adequate pre-grazing herbage mass or intensive grazing. The impact on enteric CH_4 mitigation, when scaled per unit of animal product, should be greater when animals consume higher quality forage.

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 DM (Tyrrell *et al.*, 1992; Boadi and Wittenberg, 2002). A study from western Canada (Ominski *et al.*, 2006) using the SF_6 technique demonstrated that growing beef cattle consuming all-forage diets during the winter feeding period will lose 5.1 to 5.9 percent of the feed GEI as CH_4. In some cases, however, these losses can be as high as 10 to 11 percent of GEI with low-input grass pastures, which is much higher than the average Y_m factor of 6.5 percent used by IPCC (2006a). Grazing management, improving pasture quality and supplemental feeding during the cow-calf stage have been shown to contribute to reducing duration of this phase of a beef cattle cycle that produces up to 80 percent of the GHG in the typical North American beef production system (Beauchemin *et al.*, 2011).

In a modelling study with breeding beef cattle, higher forage digestibility lowered DM intake because the cattle required less feed to meet their energy requirements, which in turn decreased GHG emissions by 5 percent (Beauchemin *et al.*, 2011). Interestingly, however, Pinares-Patiño *et al.* (2003) reported no effect of stage of maturity of timothy (early vegetative, heading, flowering and senescence) on CH_4 emissions from Charolais cows.

However, results on forage quality are often contradictory. Hart *et al.* (2009), for example, reported no difference in enteric CH_4 production when corrected for intake or rumen fermentation variables from beef cattle offered a high- or low-digestibility sward. Corn silage maturity did not affect CH_4 emissions in a study by Nishida *et al.* (2007).

An interesting meta-analysis by Archimède *et al.* (2011) investigated differences in CH_4 production by C3 vs C4 grasses and warm and cold climate legumes. The database contained 22 *in vivo* studies with a total of 112 observations. The authors used only studies in which 100 percent forage diets were fed and included tannins as a main factor in the legume model. The conclusion of this analysis was that ruminants fed C4 grasses produced 17 percent more CH_4 (per kg of OM intake) compared with animals fed C3 grasses, and animals fed warm climate legumes produced 20 percent less CH_4 than animals fed C4 grasses. This is not entirely surprising because, on average, C4 grasses in the database had about 16 percent higher NDF content than C3 grasses (64.6 vs 55.7 percent, respectively), and the greater methanogenic potential of structural vs non-structural carbohydrates is well-documented (Moe and Tyrrell, 1979). There was no difference in CH_4 production between C3 grasses and cool-season legumes. Based on this, the authors recommended use of legumes in warm climates as a strategy to reduce CH_4 emissions. Although legumes can have a CH_4 mitigation potential, problems of low persistence in pastures and the need for long establishment periods are important agronomic constraints to widespread use of legumes in a warm climate.

Unquestionably, increasing the quality, or digestibility, of forage will increase production efficiency and this will likely result in decreased enteric CH_4 emissions intensity. Keady *et al.* (2012) recently provided a comprehensive review of the effects of silage quality on animal performance in various production systems in Ireland. These authors concluded that a 10 g/kg increase in digestible OM concentration of grass silage DM could increase:

1. Daily milk yield of lactating dairy cows by 0.37 kg;
2. Daily carcass gain of beef cattle by 28 g/head;
3. Daily carcass gain of finishing lambs by 10 g/head;
4. Lamb birth weight by 0.06 kg; and
5. Ewe weight post lambing by 1.45 kg. They also pointed to the critical effect of maturity on grass silage digestibility; each one week delay in grass harvest reduced digestibility by 3 to 3.5 percent units.

An important factor that has not been discussed at length in the current document is forage preservation. There are comprehensive reviews on silage preservation, preservatives and silage best management practices[15] that discuss the importance of proper silage management for improving animal performance. The conclusion is that digestible DM lost at harvest or in the silo due to normal fermentation losses, will translate into reduced animal performance and increased GHG Ei.

Silage preservatives in general, and bacterial inoculants in particular, are of critical importance for preserving forage nutrients and consequently promoting production responses (Muck, 2012). In their review, Keady *et al.* (2012) concluded that the use of bacterial inoculants across a wide range of ensiling conditions and of formic acid under difficult ensiling conditions is expected to increase animal performance. Furthermore, there is indication that silage lactic acid bacteria-based inoculants may survive in the ruminal environment and perhaps positively affect fermentation, for example, buffering rumen pH and oxygen scavenging (Weinberg *et al.*, 2003; Hindrichsen *et al.*, 2012).

Some silage lactic acid bacteria strains, *Lactobacillus plantarum*, have been shown to reduce CH_4 production from ensiled TMR (Cao *et al.*, 2010). Another study from the same group, Cao *et al.* (2011), reported similar results with the same inoculant strain and vegetable residue silage. Increased biomass with inoculated corn and alfalfa silages was

---

[15] See Gordon (1989); Spoelstra (1991); Muck (1993); and Charmley (2001).

reported by Contreras-Govea *et al.* (2011). In some cases, even if silage fermentation was not affected, silage inoculants appeared to trigger animal production responses (Weinberg and Muck, 1996). An animal trial with one of the inoculants consistently resulting in animal production responses (*L. plantarum* MTD/1) showed increased milk production with the inoculated alfalfa silage, improved N utilization and likely increased microbial protein synthesis in the rumen, compared with the untreated silage (Muck *et al.*, 2011). Real-time polymerase chain reaction (PCR) found elevated levels of *L. plantarum* in the rumens of cows consuming the inoculant-treated silage (Mohammed *et al.* 2012).

Some studies have indicated reduced enteric CH_4 production with corn vs grass silages. A report by the United Kingdom Department for Environment, Food and Rural Affairs (DEFRA, 2010) indicated a 13 and 6 percent reduction in CH_4 per unit of DMI and per unit of milk output, respectively, when feeding a 25:75 grass silage:corn silage diet compared with a 75:25 grass silage:corn silage diet. Urinary N excretion also tended to be reduced with the higher corn silage diet. The high corn silage diet tended to increase milk yield (by about 4 percent, which resulted from increased feed intake), although the difference was not statistically significant. Another comparison of corn vs grass silage reported similar results (Doreau *et al.*, 2012).

A comprehensive overview of the various aspects of feeding corn vs legume vs grass silages for lactating dairy cows was recently offered by Dewhurst (2012). From this review it appeared that the lower fibre content and higher passage rates of legumes should result in decreased CH_4 production compared with grasses, which was reported in earlier studies (Waghorn *et al.* 2006; McCaughey *et al.* 1999) and recently by McCartney *et al.* (2012) using a methanogen marker (archaeol). These results, however, have to be confirmed in animal production studies which has not been the case with diets with relatively low inclusion of legumes (e.g. 40 percent) of the forage mixture (Van Dorland *et al.*, 2008).

As pointed out by Dewhurst (2012), the specific case of GHG emissions from silages with inhibited fermentation, typically acid-preserved, is complicated by the increased enteric CH_4 production with the inhibited fermentation silage (vs extensively fermented silage; Cushnahan *et al.*, 1995). Overall, Dewhurst (2012) concluded that corn silage-based diets are expected to result in greater DMI and milk production in dairy cows and similar trends, although less conclusive, have been reported for legume vs grass silages.

There is little research on the effect of different silages on enteric CH_4 production and whole-farm GHG emissions. Although corn silage, due to its greater starch content, is expected to reduce enteric CH_4 production, this has not been demonstrated in animal trials and, as pointed out by Dewhurst (2012), more research is needed to elucidate the effect of various silages on CH_4 production, particularly in the case of legume silages that have the additional benefit of reducing C intensity of production by replacing inorganic N fertilizer. The potential increase in total C footprint due to change in land use and increased fertilizer inputs associated with corn silage production vs permanent pasture should be also considered (Vellinga and Hoving, 2011; Van Middelaar *et al.*, 2012).

Corn silage inclusion in alfalfa silage-based diets for dairy cows can also improve animal production (Dhiman and Satter, 1997; Groff and Wu, 2005) and N efficiency (Wattiaux and Karg, 2004), which might lead to decreased N losses in urine and N_2O emissions from manure application. In traditional grass silage-based production systems, such as in Ireland for example, corn silage has been shown to increase performance of finishing beef cattle and lambs under a certain crop management scenario (complete cover plastic mulch system; Keady *et al.*, 2012). Other alternative crops, such as whole crop wheat silage, have not been beneficial, but studies with silage legumes have demonstrated improvements in ADG, food conversion and N use efficiency in lambs offered red clover, alfalfa and kale silages compared with those offered traditional ryegrass silage (Keady *et al.*, 2012).

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 percent reduction of projected CH_4 annual emissions from beef cattle. In other studies, however, stocking rate of heifers on pasture did not have an effect on CH_4 emissions (Pinares-Patiño *et al.*, 2007).

The effects of pasture composition on enteric CH_4 emissions have been extensively studied, particularly in countries in which the production systems are pasture-based, but the effect does not appear to be consistent. 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. Earlier studies by Waghorn *et al.* (2002) showed sheep fed white clover, *Lotus pedunculatus*, and other legumes had much lower CH_4 yields (12 to 16 g CH_4/kg DMI in the case of white clover) compared with sheep fed ryegrass at 21 g CH_4/kg DMI.

In another study from the same region, increasing the proportions of white clover (vs perennial ryegrass) resulted in linear increase in DMI and reduction in CH_4 production per kg DMI (Lee *et al.*, 2004). Yields of milk and milk solids also increased as the proportion of white clover increased from 0 to 60 percent. These data, however, were not confirmed by Hammond *et al.* (2011), who reported no difference between white clover and ryegrass on CH_4 yield in sheep. Methane yields for both forages declined by 6.3 ± 1.50 g CH_4/kg increase in DMI and the reduction in CH_4 yield was about 4.2 g CH_4/kg DMI for each multiple of ME for maintenance intake increase, which again emphasizes the importance of increasing animal productivity to reduce CH_4 output per unit of product. As stated by these authors, the relationship between forage intake and CH_4 yield per unit of DMI requires more investigation because it offers an opportunity to lower CH_4 emissions and at the same time increase animal productivity.

There has been moderate interest in the so-called "high-sugar grasses" (HSG; perennial ryegrass diploids with elevated concentrations of water-soluble carbohydrates) as a tool for mitigating the environmental impact of livestock. A recent review (Parsons *et al.*, 2011) concluded that "a considerable amount of research is needed to demonstrate a consistently high expression of the trait and to demonstrate reliably the potential for yield gains and reduced N loss. Associated reductions in N_2O emissions (a potent GHG) are yet to be confirmed. Even more uncertain is the prospect for reducing CH_4 emissions, whether per hectare or per unit energy intake or animal product". The authors further indicated that, "The trait remains one of very few low-cost tools being investigated for its potential to mitigate the environmental footprint of livestock production".

Similar efforts are under way in Australia with high-fructan grasses or pasture with increased digestibility (http://www.dairyfuturescrc.com.au/improving-pastures/dayesigner-grasses.htm; accessed on 11 May 2012). In the United States, research with so-called

AM and PM hay (i.e. hay harvested in the morning or in the afternoon with low- and high-sugar content, respectively) has demonstrated that animals (sheep or cattle) have a preference for PM hay (due to its higher sugar content; Burritt *et al.*, 2005; Shewmaker *et al.*, 2006), which in a Canadian study increased milk yield of dairy cows (Brito *et al.*, 2008). However, there was no effect on intake or milk production of dairy cattle when allocated to fresh grass in the morning or afternoon in a study by Abrahamse *et al.* (2009).

High-sugar forages can reduce N excretions with urine and potentially have a measurable impact on NH_3 (and N_2O) emissions from manure. Miller *et al.* (2001) reported that dairy cows on a high-sugar perennial ryegrass variety excreted a remarkable 29 percent less urinary N, and the summary of the literature by Parsons *et al.* (2011) suggested similar effects, although to a lesser extent.

Limited research has been conducted to date to determine the effect of high-sugar forages on enteric CH_4 production. A study with lambs utilizing three mixed-cultures of high water soluble carbohydrate perennial ryegrass varieties with or without white clover reported a 20 to 25 percent decrease in CH_4 emissions when expressed per unit of DMI or ADG (DEFRA, 2010). In another study from the same group, absolute CH_4 emissions were reduced (by about 24 percent) compared with the control grass; ADG in this trial was also increased (by about 30 percent) for the high-sugar grass mixture. The conclusion was that high-sugar grasses have the potential to increase the efficiency of microbial growth in the rumen, leading to an improved capture of feed N into microbial protein and diverting hydrogen away from CH_4 production and into microbial cells (DEFRA, 2010).

On the other hand, a recent simulation effort suggested that high-sugar grasses may actually increase CH_4 emissions, but this depends on the diet composition (for example, if sugars replace CP, NDF, or both), DMI and the units chosen to express CH_4 emissions (Ellis *et al.*, 2012a). Although these results are inconclusive, they are in line with experimental evidence by Hindrichsen *et al.* (2005). The latter fed dairy cattle diets in which the concentrates were either rich in lignified or non-lignified fibre, pectin, fructan, sugar or starch. Multiple regression analysis suggested that digested sugar enhances enteric methanogenesis compared with all other digested nutrients.

In many pasture-based production systems, the most benefit in terms of GHG emissions reduction can be achieved if combinations of mitigation practices are adopted. For example, mitigation “packages” for the cow-calf stage of rangeland beef production systems in Latin America might include: introducing of improved grass and legume species, strategic concentrate supplementation, improving access to water, reducing the distance animals have to walk, rotational grazing, planting trees for shelter, improving animal health and improving reproductive management (i.e. reducing the unproductive period of an animal’s life). As an example, the improvement of just 30 million ha of grasslands (i.e. less than 10 percent of the total grassland area in Latin America) by introduction of species with higher productivity and feeding quality would increase production by 4 to 5 Mt of beef per year and a reduction of more than 100 Mt CO_2-eq/yr in GHG emissions, measured in terms of intensity (equivalent to 10 percent of current total livestock emissions in the region), plus the sequestration of C in soil of another 100 Mt CO_2/yr over a period of 20 to 30 years (Daniel Martino, Executive Director, Carbosur, Uruguay; personal communication, 2012).

Overall, increased forage digestibility is expected to increase animal production and decrease enteric CH_4 emission intensity. Compared with C3 grasses, C4 grasses produce greater amount of enteric CH_4 and it appears that introduction of legumes in warm climates may offer a mitigation opportunity, although low persistence and a need for long establishment periods are important agronomic constraints. Enteric CH_4 emission may be reduced when corn silage replaces grass silage in the diet. Legume silages may also have an advantage over grass silage due to their lower fibre content and the additional benefit of replacing inorganic N fertilizer. With all silages, effective preservation will improve silage quality and reduce GHG emission intensity. Forage with higher sugar content (high-sugar grasses or harvested in the afternoon) may reduce urinary N losses and consequently, N_2O emission from manure applied to soil, although more research is needed to support this concept. The best mitigation option in this category is to increase forage digestibility in order to improve intake and animal productivity, thus reducing overall GHG emissions from rumen fermentation or stored manure per unit of animal product.

Feed processing

Feed processing for ruminant or non-ruminant farm animals is aimed at increasing feed ME, intake and animal productivity. 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. Forage processing must be balanced between enhancing passage rate to increase intake and utilization of easily-digestible nutrients, which may not be easy to achieve for lower-quality feeds. In addition, the economics of processing must be considered. Processing of whole-crop corn for silage, for example, enhances silage quality and reduces DM losses, increases both starch and fibre digestibility, and results in increased milk yield in dairy cows (Johnson *et al.*, 1999), factors that offset silage processing costs. Processing, through its effect on digestibility, energy losses and passage rate can also be an effective enteric CH_4 mitigation practice (although it may be economically infeasible in some production systems). Hironaka *et al.* (1996), for example, showed that pelleting of alfalfa can reduce CH_4 production, but this was not economically feasible due to increased production costs and was likely to be not particularly environmentally friendly due to increased energy input.

Grain processing can be a key factor in improving feed efficiency and reducing GHG emissions from livestock operations. Corn processing can have a significant impact on starch gelatinization and digestibility, although the relationship may not be linear (Svihus *et al.*, 2005). Summarizing the corn (and sorghum) processing literature, Theurer *et al.* (1999) reported increased total tract starch digestibility of steam-flaked vs steam-rolled corn grain. This improvement in digestibility resulted in an approximately 6 percent increase in milk yield in dairy cows at similar DMI, which would translate into improved feed efficiency. A recent study by Hales *et al.* (2012b) with steers in respiration calorimetry chambers compared dry-rolled vs steam-flaked corn and reported increased digestibility and about 17 percent less CH_4 emission (per unit of DMI) with the latter treatment. Per unit of DEI, CH_4 energy was decreased by 21 percent (3.30 vs 4.18 percent) and Y_m was decreased by about 19 percent (2.47 vs 3.04 percent) by steam-flaking. Although these effects are logical, grain processing may interact with fibre digestibility. Based on an extensive meta-analysis, Firkins *et al.* (2001) concluded that grain processing to enhance starch digestibility in the rumen will have a negative effect on NDF digestibility. Compensatory postruminal starch digestion may result in relatively similar total tract OM digestibility, thus diminishing the benefits of grain processing on ruminal starch digestion. Starch degradability in the reticulo-rumen results in substantial losses of feed GE (Harmon and McLeod, 2001) and thus, energetically, starch digestion in the small intestine is a more efficient process (Harmon *et al*., 2004). Ruminal degradability of starch may be up to 75 to 80 percent (Harmon *et al*., 2004). Up to 85 percent (Huntington, 1997), or an average of 35 to 60 percent (Harmon *et al*., 2004), of the starch entering the duodenum may be potentially digestible in the small intestine. Another 35 to 50 percent of the starch that escapes small intestinal digestion may be further degraded in the large intestine (Harmon *et al*., 2004). The capacity to digest starch in the intestine, however, is limited by the supply of pancreatic amylase and increasing starch flow to the small intestine (as with under-processed grain) may result in decreased total tract starch digestibility (Theurer, 1986; Huntington, 1997). In dairy cows, ruminal starch degradability was approximately 75 percent at low starch intakes and decreased to 60 percent when cows consumed above 4 kg/day starch (Patton *et al*., 2012).

An example of the importance of optimal grain processing for achieving maximum animal performance can be seen with barley grain fed to feedlot cattle. Barley's starch- and protein-laden endosperm is surrounded by a pericarp encased in a fibrous hull, both of which are extremely resistant to damage by chewing and microbial degradation, so the grain must be processed for inclusion in cattle diets (Beauchemin *et al.*, 1994). However, barley might lack kernel uniformity, which becomes a major concern for efficiency of rolling. Commercial feedlots commonly blend barley with a light bushel weight with heavier bushel weight barley to create a mid-weight barley mix that is more marketable. Although blending produces what is perceived to be a higher quality product, it actually reduces kernel uniformity and makes the achievement of optimal processing more difficult. Up to 25 percent of the faeces in southern Alberta feedlots (a primary feedlot cattle production area in Canada), for example, were found to contain undigested barley grain (Beauchemin and Rode, 1999). This means that a considerable amount of the feed nutrients are lost in manure.

Recently, Yang *et al.* (2012) examined the ability of precision processing[16] to overcome the problem of inadequate processing due to poor kernel uniformity. Precision processing was compared with conventional processing (i.e. blend of light and heavy barley and rolling with one roller setting). Feed intake and digestibility were improved with precision processing, ADG of cattle was predicted to be improved, and feed conversion ratio (feed per gain) was reduced from 6.3 to 5.8 kg/kg with steers fed the precision-processed feed compared with steers fed conventionally-processed barley. Consequently, it was estimated that cattle would stay in the feedlot 25 days less and save 163 kg feed per animal by feeding the precision processed barley grain. The reduction of CH_4 emissions from this particular example would be significant.

However, as discussed earlier in the section on *Concentrate inclusion*, the effect of grain processing may depend on the level of inclusion in the diet. When the precision processed

---

[16] Roller settings are adjusted according to the degree of kernel uniformity.

barley grain from Yang *et al.* (2012) was fed to lactating dairy cows at lower inclusion rate, there was no improvement in feed intake, digestibility or cow productivity.

> *The processing of grain to increase its digestibility is likely to reduce enteric CH_4 production per unit of animal product. Caution should be exercised that this does not result in decreased fibre digestibility. This mitigation practice may not be economically feasible in low-input production systems, but minimal processing is recommended, so the grain energy is better utilized for animal production.*

Mixed rations and feeding frequency

Very little research is available on the effect of feeding system, i.e. component or choice feeding forage and concentrates vs TMR on CH_4 production. The advantages of complete rations (i.e. TMR) have been discussed (Coppock, 1976) with perhaps the biggest advantages being a more precise nutrient allocation and a more precise feeding of micro-nutrient supplements. Nocek *et al.* (1986) fed dairy cows forage and concentrates separately or as TMR and observed higher fat-corrected milk efficiency with the separate feeding system due to lower feed intake. This kind of research is important to determine feeding regimes that improve feed efficiency, lower CH_4 emissions and decrease feed costs for developing countries.

Maekawa *et al.* (2002) did not report any differences in feed intake or milk production and composition of dairy cows fed ingredients as a TMR or separately. They concluded that the latter increased the risk of acidosis, because cows ate a greater proportion of concentrate than intended (overall rumen pH tended to be lower when compared with the 50 percent forage/50 percent concentrate TMR). Yurtseven *et al.* (2009) fed sheep a diet as a TMR or free choice (i.e. components of the diet fed separately) and reported decreased CH_4 production (per animal and per unit of DMI) with the free choice feeding system. However, these data are questionable because the published chemical analysis of the diets showed higher NDF and lower fat content of the TMR system, which would explain the differences in CH_4 production.

A study by Bargo *et al.* (2002) compared three feeding systems for lactating dairy cows:

(1) pasture plus concentrate, (2) pasture plus TMR (supplementation of pasture with a TMR, i.e. partial TMR), and (3) TMR (non-pasture). Cows fed TMR consumed more feed and produced more milk than cows fed pasture or partial TMR. Feed efficiency estimated from the published data was higher for TMR compared with pasture and partial TMR (1.37 vs 1.25 and 1.23 kg FCM/kg DMI).

Some non-traditional approaches, such as fermenting the TMR before feeding, appear effective in mitigating enteric CH_4 (Cao *et al.*, 2010), hypothetically through increased lactate intake and conversion of lactate to propionate in the rumen. Apparently, this is a common practice in Japan, aimed at preserving TMR with high inclusion rate of wet feeds. Reports have indicated that ensiled TMR has greater aerobic stability due to lactic acid fermentation (Nishino and Wang, 2012), which is in line with the reported decreased CH_4 production by Cao *et al.* (2010).

Very few studies have investigated the effect of feeding frequency on enteric CH_4 emission. The reason for including this discussion in relation to CH_4 emission is that synchronization of energy and protein availability in the rumen has long been proposed as a tool for optimizing rumen function and maximizing microbial protein synthesis. An extensive

PENNSYLVANIA STATE UNIVERSITY, A.N. HRISTOV

photo 5
Intensive dairy production system in the western United States utilizing mixed rations (open-lot type dairy)

discussion of this topic was published in Hristov and Jouany (2005), who concluded that there was not enough evidence to support the practicality of the synchronization concept.

Some of the earlier studies investigated the effect of feeding frequency from the perspective of optimizing carbohydrate fermentation in the rumen. Mathers and Walters (1982), for example, fed sheep every two hours and concluded that, even with frequent feeding there was considerable deviation from steady state in the rate of carbohydrate fermentation in the rumen. Methane production increased rapidly, within 30 minutes, after feeding and then decreased until the next two-hour cycle.

A series of trials in the 1980s from the laboratory of M. Kirchgessner in Germany found that frequent feeding did not improve dietary energy use but did increase CH_4 emission when concentrate was fed more often and separately from forage or with higher CP diets (Muller *et al.*, 1980; Röhrmoser *et al.*, 1983).

More recently, feeding frequency had no effect on CH_4 production in dairy cows (Crompton *et al.*, 2010). Cows do tend to consume more feed when it is freshly delivered (DeVries and von Keyserlingk, 2005), but in the Crompton *et al.* (2010) study, in the once per day feeding treatment, CH_4 production peaked at 140 minutes after feeding and steadily decreased (at a rate of −0.0007/min) thereafter.

The literature on the effect of feeding frequency on animal production is also scarce. Dhiman *et al.* (2002), for example, did not report any production advantage of feeding lactating dairy cows once or four times daily. In some cases, milk production of dairy cows was reduced with frequent feeding, and this was attributed by the authors to more frequent handling (Phillips and Rind, 2001).

> *There is little evidence of beneficial effects of synchronizing energy and protein delivery or frequency of feeding on ruminal fermentation and specifically CH_4 production. Feeding of total mixed rations may have some advantages over component feeding in stabilizing ruminal fermentation and dry matter intake.*

Precision feeding and feed analyses

The original term "precision agriculture" was coined in relation to plant nutrition, namely "a series of technologies that allow the application of water, nutrients and pesticides only to the places and at the times they are required, thereby optimizing the use of inputs" (Day *et al.*, 2008; Godfray *et al.*, 2011). In animal nutrition, precision feeding may have different dimensions, but from a practical standpoint and farm sustainability perspective it refers to matching animal requirements with dietary nutrient supply.

Accurate prediction of animal requirements and accurate feed analyses go hand-in-hand with minimizing feed waste, maximizing production and minimizing GHG emissions per unit of animal product. The importance of not overfeeding protein to reduce NH_3 and N_2O emissions from manure is discussed in the following sections. Precision feeding would likely have an indirect effect on enteric CH_4 emission through maintaining a healthy rumen and maximizing microbial protein synthesis, which is important for maximizing feed efficiency and decreasing CH_4 emission per unit of product.

As discussed in the following sections, simulation analyses have raised the possibility of increasing enteric CH_4 production per unit of DMI if dietary protein is replaced with carbohydrates. It is also possible that CH_4 emissions from stored manure may increase if rumen N availability is below the needs for optimal rumen function, resulting in increased excretion of fermentable OM (NDF, starch) in manure.

Precision feeding requires feed resources, equipment and management discipline in intensive animal production systems. It may be impossible to achieve in subsistence animal production systems in many developing countries where the majority of subsistence farmers do not keep livestock solely for the production of meat or milk, and consequently, livestock are often maintained at maintenance on crop or household residues. In addition, for those subsistence and extensive farmers specializing in animal production, lack of understanding of the nutrient requirements of native, multi-purpose breeds of animals, lack of consistent quality feed resources, and lack of easily accessible and affordable feed analysis services, hampers precision feeding.

Nevertheless, there are examples of the positive effects of proper diet formulation on animal productivity and enteric CH_4 mitigation in developing countries. In a field experiment in India (Gujarat state), Kannan and Garg (2009) balanced diets for lactating buffaloes and cows (replacing energy with protein) resulting in a significant decrease in CH_4 emission from both species and at the same time an increase in milk production and milk fat content (at similar DMI). In a later study from the same group, Kannan *et al.* (2011) balanced the ration of lactating crossbred cows for CP, Ca, and P and reported increased milk yield and reduced CH_4 production. Calculated microbial N supply was also significantly increased after balancing the ration.

Garg *et al.* (2012) documented remarkable progress in animal performance utilizing a programme to feed balanced rations to lactating cows (n = 540) and buffaloes (n = 1 131) in India. Evaluation of the nutritional status of animals showed that for 71 percent of the animals, protein and energy intakes were higher, and for 65 percent Ca and P intakes were lower than the requirements. Balancing the rations significantly improved milk yield by 2 to 14 percent and milk fat by 0.2 to 15 percent. Feed conversion efficiency, milk N efficiency and net daily income of farmers also increased as a result of the ration balancing. Thus,

PENNSYLVANIA STATE UNIVERSITY, A.N. HRISTOV

photo 6
Corn silage (left) and alfalfa hay (right) on a Western United States dairy farm

it is of paramount importance that science-based feeding systems and feed analysis are gradually introduced into developing countries with subsistence animal agriculture. This will not only have a measurable economic benefit for the farmer, but will also help maximize production and feed utilization, and consequently reduce GHG livestock emissions.

Accurate analysis of feed composition is the first step in the precision feeding process. Even in developed countries with established feed analysis networks, there is still substantial variability in feed analysis among commercial laboratories (Hristov *et al.*, 2010a; FAO, 2011b). In intensive dairy systems, for example, day in and day out control of forage, particularly silage DM, can have a profound effect on precision feeding of the cow for maximum production and profitability.

A rain event in a bunker silo can affect milk production by up to 3 kg/day per cow due to inaccurate dietary DM and nutrient supply to meet production needs (Lee, 2012). In situations like this, or when moisture of the forage changes, adjustments must be made on the basis of DM content so that a more consistent diet can be fed. Recently developed feed analysers based on near-infrared reflectance spectroscopy (NIRS) technology that can be mounted inside a payloader bucket can read the DM content of the forages (and grain) and also measure protein, starch, ADF, NDF, EE and ash values. The feed analysis is then sent to one or multiple computers loaded with feed management software which, on calculation, submits new instructions to a high-tech weighing controller that adjusts the amount of feed that enters the TMR mixing wagon by weight.

Such precision in mixing feed ingredients on the farm, although perhaps not refined yet and not practical for many production systems, should produce a consistent diet and result in increased milk production and greater feed efficiency, which will eventually translate into optimal rumen function, animal health and longevity.

The NIRS technology has developed rapidly since the late 1980s and for the past two decades has been used routinely for quality and component analysis of grain, oilseeds and forages. The advantages and limitations of the technique have been discussed elsewhere (Givens and Deaville, 1999).

The speed of analysis makes NIRS feasible for producers to buy ingredients based on quality and to formulate rations accurately to meet the nutrient requirements of the animals to minimize over- or under-feeding. Animal nutritionists have started to use NIRS to evaluate feed digestion and animal performance. De Boever *et al.* (1997) assessed application of NIRS for predicting ruminal *in situ* degradability of feeds and reported favourable prediction potential of NIRS. Efforts have also been made to develop calibration equations for measuring kinetic parameters of nutrients by using *in vitro* methods as a reference (Herrero *et al.*, 1996; Andres *et al.*, 2005). Nousiainen *et al.* (2004) used the *in situ* method as a reference for measurements of indigestible NDF (as predictor of feed digestibility) and concluded that NIRS has potential for predicting *in situ* indigestible NDF of grass silage. Similarly, Nordheim *et al.* (2007) demonstrated the potential of NIRS to predict *in situ* NDF degradation characteristics in roughages covering a wide range of forage species and conservation techniques.

In Australia, faecal NIRS calibration equations have been developed to estimate CP concentration, DM digestibility of the diet and BW change of cattle grazing tropical pastures (Coates, 2004), providing a rapid, economical and objective evaluation of nutrient intake by grazing cattle.

The NIRS technology could be potentially used not only for traditional analyses of nutrient contents of feeds but also for determining feed digestibility in the rumen and in the total digestive tract and animal performance. Thus, NIRS could be a viable tool for accurate analysis of feed composition and digestibility, proper diet formulation and improved feed utilization, which will inevitably result in reduced GHG, specifically enteric CH_4, emissions from various livestock production systems.

> *Precision feeding, i.e. closely matching animal requirements and dietary nutrient supply, is important for maximizing feed utilization, stabilizing rumen fermentation, improving rumen and animal health, and minimizing nutrient excretion in manure. These effects of precision feeding are expected to decrease enteric and manure GHG emissions. Accurate feed composition analyses are an integral part of precision feeding but require infrastructure and investment, which may not be available in many production systems. Adoption of science-based feeding systems and feed analysis in developing countries with subsistence animal agriculture will have economic benefits for the farmer and will also help maximize production, feed utilization, and consequently reduce GHG livestock emissions.*

Mitigation options for production systems based on low-quality feeds

Low-quality feeds, such as crop residues and low-quality grasses, are important basal feeds for ruminants in developing countries (Blümmel *et al.*, 2009). Feeds available in smallholder mixed crop-livestock systems can be classified as green feeds (cultivated fodder, grass), crop residues from coarse cereals and legumes and fine cereal straws, and concentrates (grains, cakes, and bran) (Blümmel *et al.*, 2009).

Many technologies and strategies to improve the feeding value of low-quality feeds have been suggested. Devendra and Leng (2011) and Tarawali *et al.* (2011) argued that application and results of interventions to improve the feeding value of low-quality feeds should be considered in the farming system context. In developing countries, the majority of farmers operate in smallholder mixed crop-livestock systems, and almost three billion people depend on such systems for their food supply (Herrero *et al.*, 2010). In these countries, the number of intensive livestock production systems is low. To a large extent, mitigation options for CH_4 emissions for these production systems in developing countries will be similar to those for intensive systems in developed countries. However, mitigation options for smallholder mixed crop-livestock systems will differ for a number of reasons that are discussed below.

Most livestock production systems are faced with one or more seasons with low feed availability and quality, and production during such seasons is absent or even negative because animals rely solely on crop residues. During the cropping and harvesting season, more and better feeds are available, but labour limitations and grazing land availability may prevent optimal feeding (Tarawali *et al.*, 2011; Owen *et al.*, 2012). Importation of high quality feeds (concentrates and high quality forages) into these systems is very low (e.g. Blümmel *et al.*, 2009).

In the majority of smallholder mixed crop-livestock systems, the major goal is crop production and animals are simply a means to achieve this goal. Inputs of labour, capital and land are primarily aimed at crops. In these systems, livestock intensification competes with crops for inputs. Livestock in developing countries are not only valued for their production of food but also for functions such as manure production, draught, capital store and insurance (Udo *et al.*, 2011), which are functions supported by larger herd sizes.

Hardin (1968), Zemmelink *et al.* (2003), Abegaz *et al.* (2007), and Blümmel *et al.* (2009) have indicated or observed the effect of sharing an existing feed base by too many animals: availability of good and medium quality feeds is insufficient to feed the herd; low-quality feeds are included in the ration, which leads to sub-optimal individual animal productivity but also sub-optimal total herd productivity. Hence, the non-food functions of animals negatively affect herd productivity because of the too large herd sizes, which forces the extensive use of low-quality feeds.

The most relevant mitigation option for smallholder mixed crop-livestock systems in developing countries is to increase individual animal productivity as a consequence of providing better feeds. Reduction of the number of animals, particularly in subsistence production systems, allows for the provision of adequate feed to a herd selected for genetic potential that can receive suitable veterinary care (Tarawali *et al.*, 2011), leading to an improvement in individual animal and total herd production. In this scenario, CH_4 emissions will be reduced for both, the total herd and per unit of animal product. However, this mitigation option is in conflict with the interest of smallholders to have a large herd for non-production functions and risk mitigation. Hence, herd size reduction requires measures such as mechanization, use of artificial fertilizers and proper banking and insurance systems to replace the importance of the animals (Udo *et al.*, 2011). Regulatory measures (taxes and quota) could reduce the benefits of keeping too many animals. This mitigation is highly recommended because it is beneficial for livestock output and CH_4 emissions, and it lowers the impact of livestock production on the environment, water and other agricultural land use. However, its widespread adoption will be challenging because of the socio-economic reasons outlined above.

Supplying a substantial amount of relatively good quality feeds to a ration will increase individual animal productivity. Green feeds such as multipurpose leguminous fodder trees and grasses, such as Naipier (*Pennisetum purpureum*) are promising supplements with a reasonable world-wide adoption (Saleem, 1998; Mekoya *et al.*, 2008; Oosting *et al.*, 2011; Tarawali *et al.*, 2011; Owen *et al.*, 2012). However, such fodder crops compete with food crops for land and water.

A positive contribution of leguminous fodder crops to soil fertility can be expected because of N fixation. Whether polyphenols in leguminous fodder trees will have positive effects on CH_4 emissions at the inclusion levels observed in developing countries needs to be further investigated (Owen *et al.*, 2012; see *Plant bioactive compounds*).

Another kind of supplementation is the provision of relatively small amounts of nutrients that limit intake, digestion or utilization of the ration (Oosting *et al.*, 1994, 1995; Owen *et al.*, 2012). The urea-molasses multi-nutrient block developed in Asia (Sudana and Leng, 1986; Owen *et al.*, 2012) is an example of an N-providing supplement for diets low in N. The potential role of these blocks as source of CH_4 mitigating agents, i.e. nitrates, has been discussed under *Electron receptors*. Calcium, P, Cu and Zn are other nutrients that improve utilization of low-quality feeds. However, limitations of the above-mentioned nutrients mostly occur when low-quality feeds are given as the sole feed. Whenever some green feeds or concentrates are available, such limitations are less pronounced. Hence, under such conditions the direct effect of supplementation on animal productivity might be low.

Sarnklong *et al.* (2010) and Owen *et al.* (2012) have reviewed and discussed options for treatment of crop residues. Rice straw, the crop residue in these publications, can be regarded as a proxy for other low-quality feeds. Chemical treatments (e.g. urea, NH_3 or sodium hydroxide) and biological treatments (direct by growing fungi on the straw or by administering fungal enzymes to the straw) all aim to improve straw digestibility by disrupting the cell wall structure and making hemicellulose and cellulose fractions more available for rumen digestion.

Urea treatment is the most widespread treatment advocated in developing countries. Low-quality feeds are mixed with an equal weight of a 0.5 to 3.0 percent urea solution and stored under airtight conditions for at least one week. Ammonia is formed from the urea and the alkaline conditions compromise cell wall conformation and improve intake and digestibility. An additional benefit is the provision of N for further improvement of feed value.

Economics, labour needs and practical feasibility have led to poor adoption of these techniques (Schiere, 1995; Owen *et al.*, 2012) despite decades of research and extension on the subject (Sundstøl and Owen, 1984). Roy and Rangnekar (2006) described one successful case of urea treatment adoption in India, where treatment helped farmers overcome storage problems under humid conditions. But, even if socio-economic circumstances would benefit crop residue treatment, it is uncertain whether this would mitigate CH_4 emissions per unit of animal product. Of course, if forage digestibility and concomitant animal productivity are increased, CH_4 production per unit of product will decrease.

In some cases, chemical treatment may increase feed intake and digestibility but have no production effects. In a trial with crossbred beef steers, NH_3 treatment of bermudagrass hay decreased concentration of fibre fractions and increased DM digestibility, but ADG and feed conversion were not affected (Krueger *et al.*, 2008). The effect of treatment was negatively related to the quality of the feed, i.e. absolute and relative treatment effects were higher for lower quality feeds and effects were negligible above a digestibility of approximately 50 percent (Schiere, 1995).

NATIONAL DAIRY DEVELOPMENT BOARD, INDIA

photo 7
Enteric CH_4 measurement in a buffalo in India using SF_6 technique

When production responses are not achieved, treatment is regarded as a tool for maintenance of livestock, or to produce at least a small quantity of product when no green feeds are available (Owen *et al.*, 2012). It may also be noted that 100 percent of urea added to straws is hydrolyzed to NH_3 in a short span of time and a major part of the urea N is lost in the air as NH_3 on opening the bags or silos (Makkar and Singh, 1987). The release of this NH_3 is also a source of pollution and could cause adverse human health effects.

It is questionable whether treatment of crop residues significantly affects rumen fermentation. Oosting *et al.* (1993), who measured CH_4 emissions in sheep and cattle that were fed untreated and NH_3-treated wheat straw-based diets in respiration chambers, did not find any effect of NH_3 treatment of wheat straw on CH_4 production as a fraction of DEI. Neither did treatment affect molar proportions of VFA in the rumen. If animal production is increased, however, emission intensity would decrease.

Fungal treatment is promising on a laboratory scale, but process control is difficult in piles of material because of the heat from fermentation (Walli, 2011). Moreover, in feeding experiments, nutrient availability and animal utilization was not improved, which may explain why this technology was not adopted (FAO, 2011a). The loss of digestible DM and thus decreasing the feeding value of the crop during this treatment can be dramatic, rendering the process unfeasible (Lynch *et al.*, 2012).

Farmers recognize and consider straw quality in their decisions for crop cultivation[17]. Coarse straws (of millets, sorghum and maize) have better feeding quality than slender straws (of rice, wheat and barley), but also within crop species, genetic variation exists with regard to straw yield and quantity, and breeding and selection can improve straw quality and yield without compromising grain yield[18].

An advantage of breeding and selection over treatment is that no additional input of capital or labour is required. Increased use of crop residues for feeding may, however,

---

[17] See Parthasarathy Rao and Hall (2003); Schiere *et al.* (2004); and Parthasarathy Rao and Blümmel (2010).

[18] See Subba Rao *et al.* (1993); Grando *et al.* (2005); and Blümmel *et al.* (2010).

reduce soil OM content (Tarawali *et al.*, 2011). Breeding straw for improved feeding quality is highly recommended and already shows promise for increased production and reduced CH_4 intensity in southern India (Blümmel *et al.*, 2010).

Mitigation options that improve the nutritive value of low-quality feeds in ruminant diets ould increase animal and herd productivity, and consequently reduce CH_4 Ei. A reduction in herd size can result in a concomitant reduction in herd GHG emissions and increase in herd productivity, as it may be more. Constraints to mitigation options such as chemical treatment, supplementation, breeding and selection for straw quality, and reduction of herd size are mainly economic and socio-cultural. Technically, these treatments can easily be applied. However, despite a long history of research to treat low-quality feeds, there has been little uptake of this knowledge on farms.

MANURE AND MANURE MANAGEMENT

Manure management refers to manure accumulation and collection in buildings, storage, processing and application to crops. Organic wastes from animal production can be categorized as "low strength and high volume" (such as wastewater and diluted slurries) and "high strength and low volume" (such as livestock manure). "High strength" waste will typically have chemical and biological oxygen demand, total N and NH_3-N, P, and heavy metals concentration at least one order of magnitude greater than "low strength" waste.

Animal manure is a valuable resource generally containing all the essential micro- and macro-elements required for plant growth. Its application to cropland increases soil OM and improves a number of soil properties including soil tilth, water-holding capacity, oxygen content and soil fertility; it also reduces soil erosion, restores eroded croplands, reduces nutrient leaching and increases crop yields (Araji *et al.*, 2001). Long-term application of animal manure increases soil microbial biomass and activity (Witter *et al.*, 1993; Paul and Beauchamp, 1996). Spiehs *et al.* (2010) reported that using beef manure as a fertilizer, for example, significantly increased total, organic and microbial biomass N in the upper 30 cm soil profile by 78 percent, 75 percent, and 130 percent, respectively, but could also increase nitrate-N and soluble P concentrations in the upper soil horizon. In developed countries, application of animal manure to cropland is an alternative to high-energy input/high-cost synthetic fertilizer. In some developing countries, manure production has been indicated as a major reason for keeping cattle by smallholder farmers (Baijukya *et al.*, 2005).

Effective utilization of animal manure on cropland is a function of the cost associated with storing, hauling and spreading the bulky waste materials. This cost is directly related to the quantity of manure needed to satisfy the nutrient requirements of crops in a given rotation system and the location of the animal operation from the receiving field. The quantity of manure needed is a function of the nutrient content of the manure and the mineralization rate of manure OM, including losses. The mineralization rate of organic N is influenced by the properties of the manure, the properties of the soil and soil temperature. The nutrient release rate of manure is critical to calculating application rates to avoid nutrient release to surface or ground waters. Organically-managed soils receiving continuously animal manure have been characterized as having higher microbial activity, faster mineralization, greater N supply and higher plant N uptake (approximately 20 percent higher; Langmeier *et al.*, 2002). In that study, the capacity of the organic soil to supply N was even more important at later cuts (of Italian ryegrass) when N was severely limiting plant growth.

Unmanaged accumulation of organic wastes, however, may present environmental- and health-related concerns for humans and animals. Potential impacts (Gerber *et al.* 2005, Steinfeld *et al.*, 2006; EPA, 2011) include:

- Eutrophication of surface water (deteriorating water quality, algae growth, damage to fish, etc.) due to input of organic substance and nutrients if excreta or waste water from livestock production entering streams through discharge, run-off or overflow of lagoons. Surface water pollution threatens aquatic ecosystems and the quality of drinking water taken from streams. Nitrogen and P are nutrients often associated with accelerated eutrophication of surface water;
- Leaching of nitrate and possible pathogens transfer to ground water from manure storage facilities or from fields on which high doses of manure had been applied; nitrate leaching and pathogen transfer, in particular, are threats for drinking water quality;
- Accumulation of nutrients in the soil if high doses of manure are applied which can threaten soil fertility;
- Degradation of natural areas, such as wetlands and mangrove swamps;
- Greenhouse gas emissions in the form of CH_4 and N_2O (direct and indirect emissions);
- Other gaseous emissions, including NH_3, skatols and hydrogen sulphide.

When animals are intensively produced under confined conditions, accumulations of manure require appropriate management which includes collection from the production site, storage, pre-treatment, treatment, and secondary and tertiary treatment processes, or may only include storage prior to application on land or processing in another environmentally-responsible way.

Manure management systems design draws on a range of engineering disciplines including civil, chemical, environmental, sanitary and biological. In some cases, technology is transferred from other sectors, such as municipal wastewater for broader application. Manure management systems have often failed due to technical and economic viability. In countries where livestock waste is regulated, high strength organic wastes are typically recycled on land, following a nutrient management plan, because this is generally the lowest cost option and brings the highest environmental benefit. Prior to land application, waste can be treated to stabilize the organic fraction, or simply stored because it cannot be land-applied year round.

Within the context of processes, climates, waste characteristics and design implications, an extensive database of references was reviewed in relation to this section. Manure CH_4 and N_2O mitigation research has been intensively conducted in the last 30 to 40 years. However, there is still much to learn about the benefits of particular mitigation practices, the effect of combining mitigation practices, the response of environmental indicators such as nutrient conversion, volatilization, leaching, erosion, etc., and the effect on the environmental and financial performance of the production system (farm) as a whole. It is common for one environmental benefit of a technology to impact degradation processes negatively in another area. For example, a livestock waste management system may include an anaerobic process followed by an aerobic process which reduces CH_4 emissions, however, would likely increase N_2O emissions. Recognizing that N_2O has a much greater GWP than CH_4 (Solomon *et al.*, 2007), a standardized net GHG accounting process is necessary to make determinations on, and report GHG net reductions or increases.

Data related to manure CH_4 and N_2O (and NH_3) mitigation practices are summarized in Table A2 of this document (see Appendix 2). Note that these data may be specific to a unit process and may not account for losses, conversions or other differences caused by preceding processes in the process train, study duration and climatic impacts (such as winter vs summer). These data are also based on laboratory, pilot and commercial scale applications and may not have accounted for the range of temperatures found in climates where these processes are used. Thus, these factors may affect the usefulness of these practices. Costs, both for initial investment and operation and maintenance, are also not provided.

Opportunities to reduce non-CO_2 GHG emissions from ruminant manure are illustrated in Figures 6 and 7 according to the process of formation and emission of CH_4 and N_2O during the ruminant production cycle[19].

Most of the CH_4 emission resulting from manure is produced under anaerobic conditions during storage and very little following land application; manure from grazing ruminants does not produce significant quantities of CH_4 because it remains largely aerobic. The EPA (2005) report pointed out that manure produced little or no CH_4, when handled as a solid (e.g. in stacks or pits) or deposited on pasture or rangelands. Therefore, opportunities to reduce CH_4 emission are centred on preventing anaerobic conditions during storage or capturing and transforming the CH_4 that is produced if anaerobic conditions are present. Similar to enteric fermentation, anaerobic cellulose decomposition in stored manures is typically a source of CH_4. Data summarized by Chianese *et al.* (2009) indicate average CH_4 emissions from covered slurry, uncovered slurry, and stacked manure to be 6.5, 5.4, and 2.3 kg/m^2 per year, although rates vary with temperature and time in storage. Agricultural soils, with the exception of rice paddies, are generally a sink for atmospheric CH_4 (typically -1.5 kg/ha per year; Chianese *et al.*, 2009). However diffusion of CH_4 from land-applied manures is a short-lived source that disappears within a few days of application to soil (Sherlock *et al.*, 2002).

Manure contains most elements necessary for stimulating soil nitrification and denitrification processes that result in N_2O formation. Nitrification and denitrification processes resulting in N_2O formation are transient depending on the amount and form of available N (NH_4^+ or NO_3^-), oxidation-reduction potential, degradable C sources, and microbial population. As a result, the production of N_2O from soil or manure storages is highly variable, difficult to measure and even more difficult to predict.

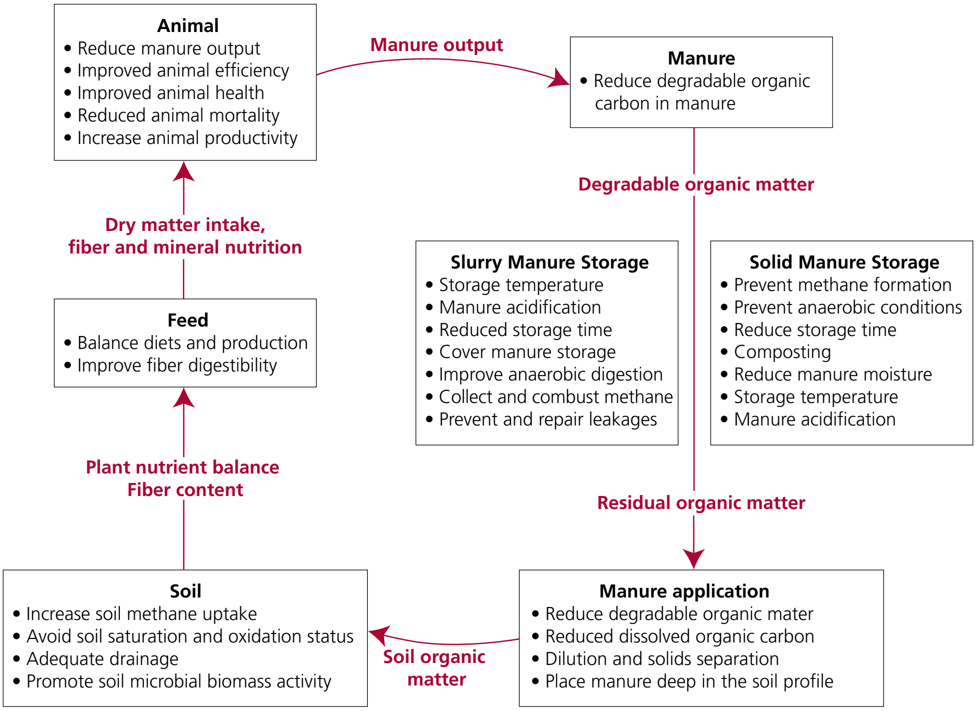
Nitrous oxide is directly produced in manure-amended soils through microbial nitrification under aerobic conditions and partial denitrification under anaerobic conditions, with denitrification generally producing the larger quantity of N_2O (EPA, 2010). Denitrifying organisms can further reduce N_2O to N_2 at rates dependent on soil conditions. 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 re-deposition (EPA, 2010). Being a result of microbial processes, the emission of N_2O is highly variable and influenced by environmental and metabolic factors, which

---

[19] See Sommer *et al.*, 2004; Rotz *et al.*, 2010; Saggar *et al.*, 2007; Giltrap *et al.*, 2010; DelGrosso *et al.*, 2000; Petersen and Sommer, 2011; Chadwick *et al.*, 2011; and Zeeman, 1994.

FIGURE 6

Flow of organic carbon through the livestock production system including opportunities to mitigate methane emissions from livestock manure



makes measurement of mitigation effects difficult. Nonetheless, results of adopting mitigation practices can be estimated by using potential N_2O emission reductions obtained when optimal conditions for nitrification and denitrification are assumed. This approach makes it possible to gauge the effect of mitigation practices and interactions within the livestock production system. Although N_2O emissions are usually low when compared with the emissions of NH_3 and CH_4, the 12:1 ratio in GWP of N_2O:CH_4 makes N_2O a potent GHG.

For direct N_2O emissions to occur, the manure must first be handled aerobically where NH_3 or organic N is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to N_2, with intermediate production of N_2O and nitric oxide (denitrification) (EPA, 2010, based on Groffman *et al.*, 2000).

Multiple factors control nitrification and denitrification rates and the ratio of N_2O to N_2 produced through denitrification. Soil temperature, water content, and oxygen concentration each influence rates of both processes, while denitrification rates are also influenced by the quantity of nitrate produced through nitrification (Cavigelli and Parkin, 2012).

Due to the nature of the antagonistic processes resulting in CH_4 and N_2O emissions (while CH_4 is produced under anaerobic conditions, production of N_2O requires sufficient levels of oxygen), some practices that result in the reduction of CH_4 production increase

N_2O emissions. An example is the aeration of manure during storage to reduce CH_4 emissions. This process may often result in an increase in N_2O emissions when aeration rate is sufficient to create an aerobic environment (Amon *et al.*, 2001).

Diet manipulation and nutrient balance[20]

Diet can have a profound effect on N losses and particularly the route of N excretion in ruminants (i.e. faeces vs urine). Diet manipulation has been shown to be an effective means to reduce NH_3 emissions from land applied manures because reduced CP in the diet produces manure with a slower mineralization rate of N (Powell and Broderick, 2011). Reducing dietary CP and ruminally-degradable protein (RDP) concentration has been recognized as an effective strategy to reduce N excretion through a marked reduction of urinary urea excretion[21], NH_3 concentration[22] and potentially N_2O emissions from dairy manure[23].

Dietary management and N_2O emissions from manure

Manure can be a significant source of N in both intensive and subsistence production systems. As pointed out earlier, in many developing countries livestock is secondary to crop production. Rufino *et al.* (2006) indicated that inclusion of the animal in the farm N cycle may result in less efficient use of N compared with direct application of crop residues to soil. Available N in manure, however, increases the immediate crop response compared with the slow nutrient release associated with mineralization of organic material. The authors suggested that efficient use of animal manure depends on improving manure handling and storage and synchronization of mineralization with crop uptake.

Digestibility of feed N is relatively high for most types of feeds, which results in faecal N being primarily of microbial origin. Van Soest (1994) pointed out that the bulk of faecal N is indigested microbial N and that endogenous secretions contribute little to faecal N losses in ruminants. Although a significant amount of protein secretions occur in the digestive tract, by the time this N reaches the faeces, it has been mostly assimilated into microbial N (Van Soest, 1994). Diets resulting in increased rumen by-pass of carbohydrates will result in a greater proportion of microbial N in faecal matter. Thus, from an environmental sustainability point of view, urinary N excretion is the important source of N_2O emissions from manure. Nitrogen excreted with urine can represent more than half of all N losses in dairy cows (Tamminga, 1992).

Urea is the main nitrogenous constituent of ruminant urine. Bristow *et al.* (1992), among others, reported that urea N represented from about 60 to 90 percent of urinary N in cattle, with similar proportions for sheep and goats. Other significant nitrogenous compounds were hippuric acid, creatinine and catabolites of purine bases, such as allantoin, uric acid, xanthine and hypoxanthine. Organic N is about 90 percent of the total N in poultry litter, with uric acid and urea being the primary organic N sources (Rothrock *et al.*, 2010). Urea is also the main nitrogenous compound in swine urine, representing 70 to 80 or more percent of urinary N (Canh *et al.*, 1997), and its excretion can be greatly increased by amino acid imbalance (Brown and Cline, 1974). In the urine of high-producing dairy

---

[20] Further discussion related to this section can be found under *Enteric Fermentation.*

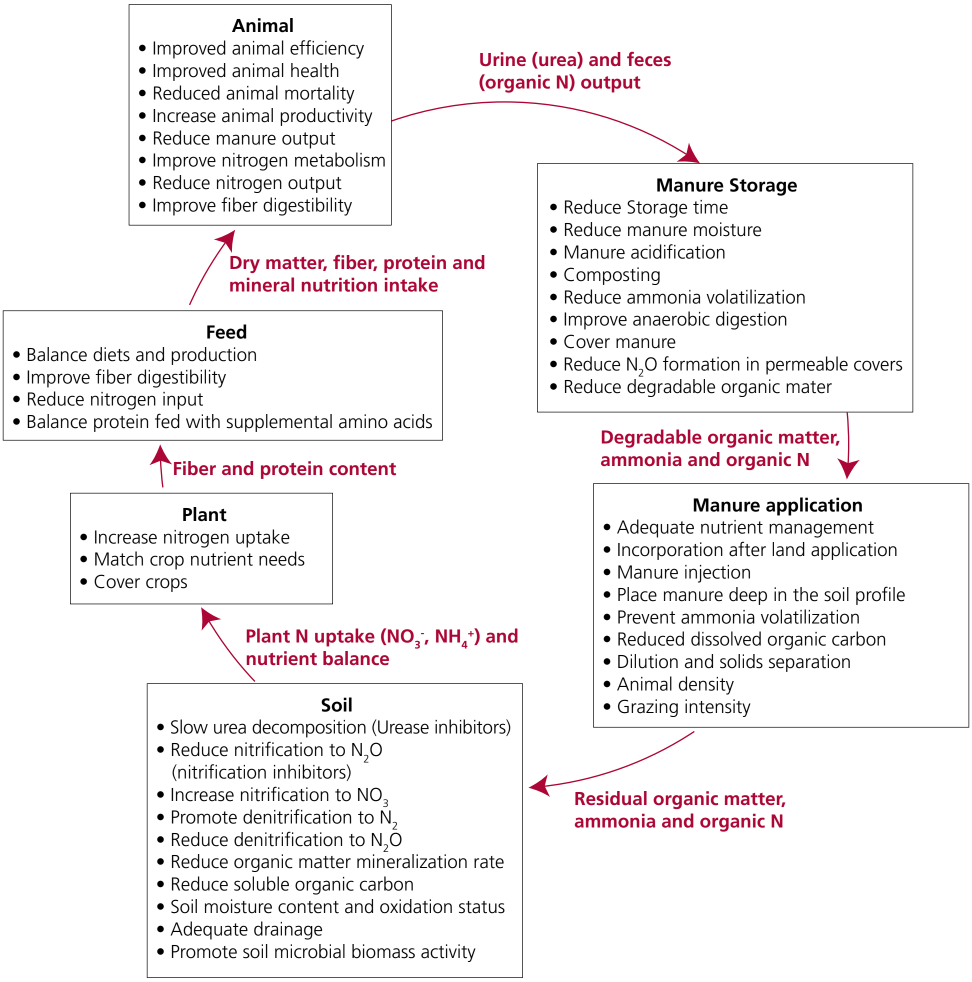
[21] See Raggio *et al.* (2004); Colmenero and Broderick (2006); and Agle *et al.* (2010a).

[22] See van der Stelt *et al.* (2008); Agle *et al.* (2010a); and Lee *et al.* (2012a).

[23] See Külling *et al.* (2001); Luo *et al.* (2010); and Lee *et al.* (2012a).

FIGURE 7

Flow of nitrogen and organic carbon through the livestock production system including opportunities to mitigate nitrous oxide emissions from livestock manure



cows, urea N represents 60 to 80 percent or more of total urinary N (Reynal and Broderick 2005; Vander Pol *et al.* 2008), and proportionally increases as dietary CP level and intake increase (Colmenero and Broderick, 2006). On low protein diets, however, urinary urea N can be as low as 46 to 53 percent of the total urinary N (Hristov *et al.*, 2011c; Lee *et al.*, 2012c). Urea is the primary source of N losses (as NH_3, nitrate, or N_2O) from cattle, small ruminants, and pig manure. Uric acid, through mineralization to urea, is the primary sources of N losses from poultry manure (Rothrock *et al.*, 2010; Hristov *et al.*, 2011a).

Urease is abundant in faecal matter or in soil, and urea is rapidly converted to ammonium, if the environmental conditions (temperature, pH) are favourable. Ammonium N is readily available to plants and can be converted, under aerobic conditions, to nitrate, which is also readily available (Beegle *et al.*, 2008). The organic forms of N in manure are generally not available to plants, unless first mineralized, which is a complex microbial process affected by various environmental factors (Beegle *et al.*, 2008).

Nitrous oxide emissions from soil application of manure are a significant contributor to the total GHG emissions from agriculture (Davidson, 2009). According to some accounts, N_2O emissions from animal waste represent 30 to 50 percent of global agricultural N_2O emissions (Oenema *et al.*, 2005). According to Luo *et al.* (2010), reduction of N_2O emissions from intensive grazing systems can be achieved by several strategies: (1) improving N use efficiency through reducing the amount of N excreted by grazing animals; (2) optimizing soil management and N inputs; (3) optimizing pasture renovation; (4) manipulating soil N cycling processes through soil additives; (5) selecting for plants and animals that maximize N utilization; and (6) altering grazing and feeding management.

Ammonia volatilization is generally the largest pathway of loss for manure N (Harper *et al.*, 2004; Lee *et al.*, 2011b), with losses typically accounting for 30 to 70 percent of the ammonium-N content of cattle manure (Thompson and Meisinger, 2002). Nitrogen emissions can also be in the form of dinitrogen gas (N_2) (Harper *et al.*, 2004). The proportion of manure N lost as N_2O is relatively low, generally below 2 to 3 percent of the manure N input and only in few reports has it reached 10 percent (de Klein *et al.*, 2001).

Because of its influence on soil oxygen concentration, soil water content has a very large impact on N_2O production. There is generally little denitrification activity below about 60 percent water filled pore space, but rates increase with increasing water content reaching a maximum at saturation (Linn and Doran, 1984). The fraction of N completely reduced to N_2 also increases as soil water content approaches saturation.

The relationship between manure NH_3 volatilization and N_2O emission is also complex because (1) emissions of both may be reduced by diet manipulation or manure management, and (2) if a mitigation technology reduces NH_3 losses, the preserved ammonium N may later increase soil N_2O emissions (Petersen and Sommer, 2011). On the other hand, gaseous losses of N will reduce the availability of N for nitrification and denitrification processes and, consequently, N_2O formation (EPA, 2010). The production of direct N_2O emissions from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system (EPA, 2010).

Dietary protein content

A comprehensive analysis by Sauvant *et al.* (2011) showed that CH_4 production per kg digested OM decreased in a linear fashion with increasing dietary CP (CH_4, g/kg digestible OM = 40.1 – 0.32 × CP, percent DM; n = 59 experiments), i.e. decreasing dietary protein concentration will likely increase fermentable carbohydrates concentration, which in turn will likely increase CH_4 production. These relationships have to be accounted for when manipulating dietary N to reduce manure NH_3 and N_2O emissions. Fibre inclusion in the diet of non-ruminants can shift the route of N excretion from urine to faeces and thus decrease NH_3 and N_2O emissions from slurry. These interactions can be complex, and ideally, effects on GHG emissions should be studied on a whole-farm scale. Care must be taken that dietary manipulations do not affect animal production or gains at one level of the production system are not offset by losses at another, e.g. animal vs manure (Jarret *et al.*, 2011; Klevenhusen *et al.*, 2011).

Effects of interactions on GHG emissions have been discussed elsewhere in this report. This section will focus on the effect of dietary protein on manure N_2O emissions. To a large extent, dietary CP concentration determines manure N concentration and can have a significant impact on N_2O emissions (Cardenas *et al.*, 2007; Luo *et al.*, 2010). Therefore, manure N (specifically readily-available urinary urea N) promotes GHG emissions from manure-amended soil.

Studies with ^{15}N-labeled urine or faeces have clearly demonstrated that urinary N is the primary source of ammonium in cattle manure, contributing from 88 to 97 percent of the NH_3-N emitted within the first 10 days of manure storage (Figure 8). Volatilization of N as NH_3 or NOx can also indirectly contribute to N_2O emissions. By far, most volatilization losses from manure are as NH_3. Although there are also some small losses of NOx, estimates of N losses due to volatilization are only based on NH_3 loss factors (EPA, 2010). As a result, urine patches are the predominant source of N_2O in grazing systems (de Klein and Eckard, 2008). Ammonia volatilized from manure can be re-deposited on soil and eventually converted into N_2O. Nitrate in leachate and soil run-off can be converted into N_2O through aquatic denitrification (EPA, 2010). According to some estimates, manure (grazing animal and managed manure) constitutes about 17 percent (or 6.7 Tg of N) of the N_2O sources in the United States (Del Grosso *et al.*, 2008). Thus, manure N and volatilized NH_3 can directly contribute to GHG emissions from animal agriculture.

Several studies have investigated the effect of dietary protein on N_2O (and CH_4) emissions from manure and manure-amended soil in trials with swine and cattle. Velthof *et al.* (2005) concluded that decreasing the protein content of pig diets had the largest potential to simultaneously decrease NH_3 and CH_4 emissions during manure storage and N_2O emission from soil. Külling *et al.* (2001) reported decreased N_2O emissions during simulated manure storage of manure from dairy cows fed low-protein diets, but the total GHG emissions were not affected by the dietary protein content (due to increased CH_4 emissions from the low-protein manure).

Data on the effect of dietary protein on manure N_2O emissions are not consistent and often no effect or even increased N_2O emissions (from housing) when lowering dietary protein have been reported for swine (Clark *et al.*, 2005; Philippe *et al.*, 2006) and cattle (Arriaga *et al.*, 2010). It must also be borne in mind that manure CH_4 and CO_2 emissions per unit of land may increase immediately following soil application (or during storage) due to the use of a greater application rate for low- vs high-protein manure to meet the crops N requirements (Lee *et al.*, 2012b).

Low-protein diets have to be formulated to meet or exceed energy requirements and meet the animal's metabolizable protein (MP) and AA requirements, if feed intake and animal performance are to be maintained (Lee *et al.*, 2011a). Diets severely deficient in RDP will reduce total tract fibre digestibility in ruminants, which may negatively affect animal performance, increase fermentable OM in manure and increase manure CH_4 emissions. On the other hand, these effects may be counteracted by reduced enteric CH_4 production because fibre degradability in the rumen will decrease. Severely deficient RDP diets will have a negative impact on microbial protein synthesis and animal productivity and therefore, cannot be recommended as a mitigation practice.

With pigs and poultry, there are numerous examples of the beneficial effects of reduced dietary protein, with or without synthetic AA supplementation, on reducing N losses and NH_3 emission from manure while maintaining productivity and improving feed conversion efficiency (Sutton *et al.*, 1996, 1999; Portejoie *et al.*, 2004; Keshavarz and Austic, 2006). Cromwell and Coffey (1993) reported a 17 to 23 percent decrease in N excretion when dietary protein was reduced by 2 percentage-units and the diet was supplemented with synthetic lysine. Research from this group indicated that further reductions in dietary protein of 3 to 4 percentage-units and supplementation with a cocktail of AA (lysine, methionine, threonine, and tryptophan) reduced N excretion by 35 percent (Carter *et al.*, 1996). A review of the swine literature pointed out that lowering dietary protein, phase-feeding, and use of exogenous enzymes (phytase in relation to phytate-P utilization, in this case) had a tremendous environmental impact in The Netherlands (Lenis and Jongbloed, 1999). These authors also concluded that decreasing dietary protein, inclusion of additional non-starch polysaccharides in the diet, and diet acidification (to decrease urine pH) can lead to a substantial reduction in NH_3 emission from swine manure. Similar to swine, a 1.3 percentage-units reduction in dietary protein resulted in a 21 percent reduction in N content of poultry manure (Meluzgi *et al.*, 2001). With laying hens, supplementation of a reduced protein diet with synthetic lysine and methionine reduced faecal N concentration by 30 percent (Latshaw and Zhao, 2011). There is also evidence (LCA and experimental) that reducing dietary protein content and supplementation with AA decreases GHG from pig manure (Ball and Mohn, 2003; Mosnier *et al.*, 2011; Osada *et al.*, 2011).

Dietary tannins (ruminants only)

Shifting N losses from urine to faeces is expected to reduce N_2O emissions from manure-amended soil due to the lower concentration of volatile N in manure[24]. Feed additives, such as tannins have been shown to redirect excreted N from urine to faeces. Carulla *et al.* (2005) reported a 9.3 percent reduction in urinary N as proportion of total N losses, and Misselbrook *et al.* (2005) reported a 25 percent reduction. Grainger *et al.* (2009a) observed a 45 to 59 percent reduction in urinary N excretion but also a 22 to 30 percent drop in milk N secretion.

As an example, Aguerre *et al.* (2010) observed a linear decrease in urinary N excretion (vs a linear increase in faecal N excretion) in high-producing dairy cows fed diets supplemented with 0 to 1.8 percent (DM basis) of a quebracho tannin extract. Ammonia emission from slurry from cows receiving the tannin-supplemented diets was 8 to 49 percent lower than emissions from the control slurry. Tannins also reduced NH_3 emission when directly applied to barn floor (by 20 percent), and after a tannin extract was applied to soil (by 27 percent; Powell *et al.*, 2011a,b).

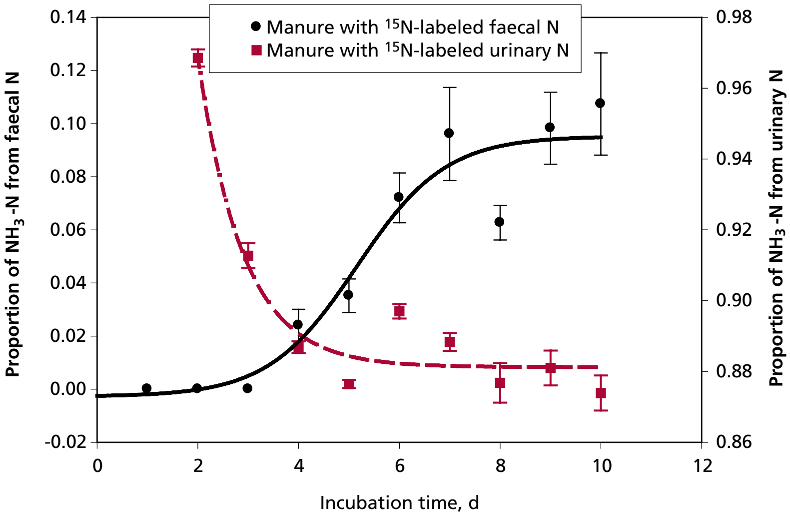
Studies directly investigating the effect of tannins on manure or soil N_2O emissions are scarce. Hao *et al.* (2011) supplemented cattle diet with condensed tannins from *Acacia mearnsii* at 25 g/kg DM and followed GHG emissions from composted manure for up to 217 days. Nitrous oxide emissions occurred during the first 56 days of composting, were generally low (up to 0.1 kg N/t compost DM), and not affected by tannin supplementation. Methane (and CO_2) emissions were also not affected by tannin supplementation.

---

[24] This will depend on storage conditions if manure is stored before application.

FIGURE 8

Proportion of ammonia-N emitted from manure originating from faecal or urinary N



Note: In this experiment, faeces or urine were labeled with ^{15}N through a continuous infusion of $^{15}NH_4Cl$ into the rumen of lactating dairy cows (data from Lee *et al.*, 2011b).

The authors speculated that tannin application level was too low, tannins were complexed with protein upon excretion in the faeces, or that microbes in compost were capable of altering the biological activity of tannins. Clearly, more studies are needed to relate tannin application, through the diet or directly to manure, to GHG emissions from manure during storage or after land application.

Shifting N excretion from urine to faeces by supplementing the diet with tannins or feeding tanniferous forages have implications on manure N availability for plant growth. Fox *et al*. (1990) studied mineralization rates of legumes as affected by their polyphenol and lignin contents in a 12-week greenhouse experiment. At the end of the trial, net N mineralization rate ranged from 11 percent with cassia (*Cassia rotundifolia* Pers., var. Wynn) to 47 percent for alfalfa. Up to six weeks, there was a linear decrease in net N mineralization rate with increasing lignin + polyphenol:N ratio of legumes. The authors concluded that the lignin + polyphenol:N ratio is an excellent indicator of mineralization rate for the first 12 weeks after soil incorporation. These data and inferences drawn by others (Palm and Sanchez, 1991) led de Klein *et al.* (2010) to the conclusion that tannin–protein complexes may be more resistant to breakdown in the soil.

Decreased N release rate from manure from animals fed tanniferous forages has been reported (Powell *et al.*, 1994; Cadisch and Giller, 2001), although other reports indicated no effect of condensed tannins on the agronomic value of cattle manure (Hao *et al.*, 2011) and decreased manure N availability may be a significant problem in agricultural systems relying exclusively on manure as a source of N for crop growth. Indeed, some reports have indicated a significant drop in yields when high-tannin manure (equivalent to 2.2 t tannins/ha per year) was added to sweet corn and radish plots; 27 to 32 percent yield reduction for sweet corn and 42 to 46 percent for radish (Ingold *et al.*, 2012). However, others reported no effect of condensed tannins on the N fertilizer value of faeces from sheep receiving a diet supplemented with tanniferous legumes (Tiemann *et al.*, 2009).

Tannins may also have other implications, such as inhibition of intestinal parasite development in faeces and soil (Niezen *et al.,* 2002). The effect of feeding tanniferous forages or supplementing the diet of ruminants with tannins on manure N availability in soil and consequent plant growth needs further investigation.

Strategies for mitigating N_2O emissions from livestock operations, have been summarized by de Klein and Eckard (2008). These authors discussed the following abatement strategies, with focus on ruminant grazing systems:

1. Dietary amendments: for example, salt inclusion through its diuretic effect dilutes N in urine and may lead to 5 to 10 percent reduction in N_2O emissions. Also supplementation of the diet with nitrification inhibitor through a slow-release bolus that is excreted unaltered in urine (30 to 60 percent N_2O reduction potential);
2. Animal breeding: selection of animals for N efficiency, generally associated with lower dietary N input and higher N output in milk or meat (3 percent reduction in urinary N excretion);
3. Reduction of dietary protein: hard to achieve in intensive pasture systems due to high N fertilizer application rates and low N utilization efficiency by the animal (10 to 45 percent potential reduction in urinary N excretion; see following discussion);
4. Dietary tannins (as feed supplements or fed through high-tannin forages): shifting N excretion from urine to faeces (up to 60 percent reduction in urinary N excretion; see related discussion under Enteric Fermentation);
5. Fertilizer management: rate, source, and timing of fertilizer application (in relation to soil moisture[25] and temperature conditions) are critical factors for reducing N_2O emissions from soil (2 to 13 percent N_2O reduction potential);
6. Nitrification inhibitors: direct application of nitrification inhibitors on the soil has a significant potential to reduce N_2O emissions resulting from urine deposition (see further discussion under Manure and Manure Management);
7. Effluent management (applicable to stored manure): timing and application method are critical for reducing N_2O emissions (50 percent N_2O reduction potential; see related discussion under Manure and Manure Management);
8. Reduction in wet season grazing (related to the critical role of soil moisture in the nitrification-denitrification processes (7 to 11 percent N_2O reduction potential);
9. Irrigation and drainage; again, related to soil moisture (up to 60 percent N_2O reduction potential);
10. Genetic engineering or selection to improve forage utilization of soil N (for example, deeper root systems, release of natural nitrification inhibitor by plants) or improve feed N conversion efficiency by the animal;
11. Animal physical intervention, e.g. more even spreading of urine in grazing systems.

---

[25] Soil moisture is an important factor in nitrification-denitrification processes; Maag and Vinther (1996).

De Klein and Eckard (2008) concluded that abatement of N_2O should be considered as part of an integrated approach to improve the efficiency of N cycling in animal production systems. Particular attention should be given to improving animal N utilization, thus reducing urinary N output to the soil-plant system. According to the authors, current technologies could deliver up to 50 percent reduction in N_2O emissions from an animal housing system but only up to 15 percent from a grazing system.

As already stated, an important opportunity to reduce N_2O emissions from animal manure is to maintain dietary protein close to animal requirements. Studies with pigs, poultry, and beef and dairy cattle have consistently shown that a reduction in dietary protein results in a reduction of excreta N losses, which results in reduced NH_3 and potentially N_2O emissions from manure[26]. Van Soest (1994) stated that the minimum concentration of CP in the diet of ruminants is 6 to 8 percent (DM basis). In high-producing dairy cows, however, these concentrations are too low to maintain production. It has been documented that decreasing dietary protein in lactating cows can lead to depressed DMI and consequently, decreased milk production (Firkins *et al.*, 2006; Lee *et al.*, 2011a).

In feeding systems, in which feed intake and diet composition can be closely controlled (i.e. TMR feeding), reducing dietary CP in dairy cows below MP requirements (NRC, 2001) has a major impact on increasing milk N efficiency (MNE, i.e. milk protein N ÷ feed N) and decreasing urinary urea N losses and NH_3 emissions from manure (Hristov *et al.,* 2011a). In dairy production systems, MNE varies largely among individual cows and herds (efficiency of imported N utilization, i.e. total N exports ÷ total N imports, on a whole-farm basis varied as much as 25 to 64 percent in large dairy farms; Hristov *et al.*, 2006) and can be used to "benchmark" the efficiency of the whole production system or as a performance indicator and policy tool for dairy production systems (Powell *et al.*, 2010).

Experiments with high-producing dairy cows have demonstrated that some feeding models (NRC, 2001, for example) may under-predict milk production when MP-deficient diets are fed. Inaccurate estimation of feed RDP, and perhaps overestimation of RDP requirements, in addition to unaccounted physiological mechanisms, such as urea recycling (Huhtanen and Hristov, 2009) and the non-linear (limiting returns) relationship that improves the efficiency of conversion of MP into milk protein (i.e. MNE) as diets become increasingly deficient in MP (Lapierre *et al.*, 2007), are likely responsible for the under-prediction of milk yield for the MP-deficient diets observed in several experiments (Figure 9). As reported by Reynolds and Kristensen (2008), the fraction of total urea production that is returned to the gut decreases in a non-linear fashion with increasing dietary CP content. Clearly, return of urea to the gut is a large potential source of ruminal N, but the net recovery as microbial N is more difficult to assess because of interactions with dietary energy sources.

Caution should be used when formulating MP-deficient diets for high-producing dairy cows or growing cattle. Røjen *et al.* (2011) and Røjen and Kristensen (2012), for example, showed that increased ruminal rate of urea-N extraction with low-protein diets was partially counteracted by decreased blood urea concentrations. Nevertheless, urea-recycling is an underutilized mechanism, and there is potential for decreasing dietary protein inputs in ruminants without jeopardizing production, thus decreasing manure NH_3 and N_2O emissions.

---

[26] See Sutton *et al.* (1999); Velthof *et al.* (2005); Kerr *et al.* (2006); and Hristov *et al.* (2011a).

To match requirements and supply and reduce N losses, dairy cows can be fed varying dietary protein concentrations throughout the lactation. Wu and Satter (2000) demonstrated that decreasing dietary CP around week 30 of lactation (from 17.5 to 16 percent, DM basis) can decrease manure N losses, maintain milk production and increase farm profitability compared with a constant 17.4 to 17.9 percent CP diet. Data from 12 commercial dairy farms in Pennsylvania (Hristov *et al.*, 2012b) showed that reducing dietary CP by 1 percent-unit (verified by rigorous feed and TMR sampling over a two-year period) increased income-over-feed cost (IOFC) on average by US$0.63/100 pounds of milk (2009-2010 data). Recommendations for reduced dietary protein should be accompanied by a clear message that low-protein diets must be well-balanced for all other nutrients, specifically energy, so that animal production is not negatively affected. Strict control over day-to-day forage composition and mixing of the diet are easier to accomplish in experimental settings than on a commercial farm, and this is an important factor that needs to be considered by academia and nutrition consultants when diets supply nutrients near animal requirements. Similar to dairy cows, dietary protein can be safely reduced at certain phases of the beef production cycle without affecting growth rates and dramatically reducing N losses. Cole *et al.* (2006) reported that performance of feedlot cattle fed a constant 11.5 percent CP diet did not differ from those fed a 13 percent CP diet. Phase-feeding of CP decreased N excretion by 1.5 to 3.8 kg/steer and N volatilization losses by 3 to 5 kg/steer. Similarly, Erickson and Klopfenstein (2010) fed CP to beef cattle at (13 percent) or below (12.1 to 10.9 percent; phase-feeding) the industry standard. Phase-fed cattle in this study excreted 12 to 21 percent less N, and N volatilization losses from the feedlot were reduced by 15 to 33 percent. In these experiments, a simple management approach such as increasing pen cleaning frequency decreased N volatilization losses by 19 to 44 percent and increased manure N by 26 to 41 percent. These strategies will not only have a significant environmental impact but will reduce feed cost per unit of product.

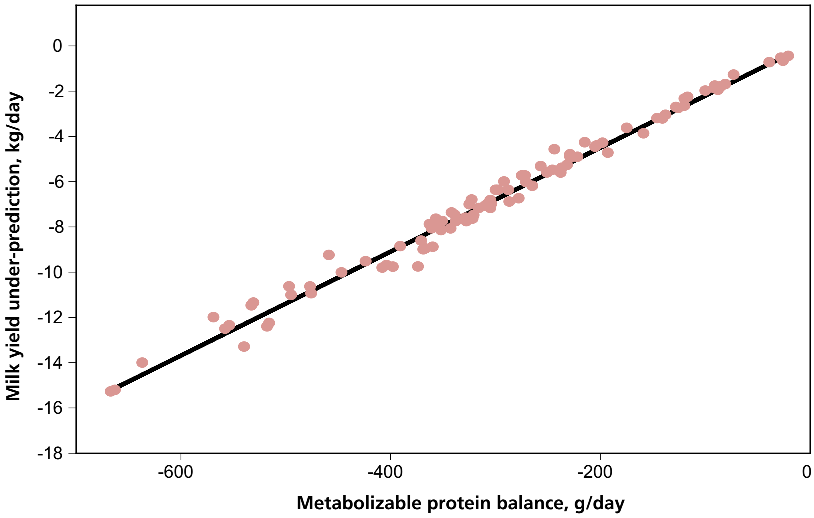
One factor that needs to be considered with low-protein diets is fibre degradability in the rumen and digestibility in the total digestive tract. A meta-analysis by Huhtanen *et al.* (2009a) showed that diet CP was the only dietary factor (of the factors studied in this analysis) that was positively related to NDF digestibility in dairy cows. Thus, reduction of dietary protein should not be to the extent that RDP and NH_3 become deficient and fibre degradability suffers.

Ruminal cellulolytic bacteria, such as *Fibrobacter succinogenes*, *Ruminococcus albus* and *R. flavefaciens*, require a certain level of degradable N (especially NH_3-N) to effectively ferment carbohydrates in the rumen (Atasoglu *et al.*, 2001). If NH_3 and RDP are severely deficient, total tract fibre digestibility will decrease (Lee *et al.*, 2011a; Aschemann *et al.*, 2012) and faecal excretion of fermentable fibre will increase, which may stimulate CH_4 production from manure. Decreased fibre degradability will also decrease DMI as a result of gut fill (Mertens, 1994), which will lead to decreased productivity. It is important to point out that this can occur only if fibre degradability in the rumen is reduced. In dairy cows, for example, dietary CP can safely be decreased to around 16 percent (from the common 17 to 18 percent in the United States; Hristov *et al.*, 2006) without a significant impact on fibre digestibility (Colmenero and Broderick, 2006).

Using mechanistic models, Dijkstra *et al.* (2011b) concluded that dietary-N mitigation options at the animal level aimed at reducing urinary N excretion may result in elevated

FIGURE 9

Relationship of metabolizable protein (MP) balance (NRC, 2001) and under-prediction of milk yield in dairy cows (From Lee *et al.*, 2012b)



enteric CH_4 emission (per kg of fat- and protein-corrected milk; FPCM). In their simulation of grass silage-based diets for dairy cows, these authors calculated that CH_4 emission was expected to increase by 0.33 g/g urinary N decrease (the authors did, however, point to a large variation in the prediction). This implies that the reduction in N_2O emission upon application of the manure with reduced N content may be partially offset by increased enteric CH_4 production. If ruminal fibre degradability suffers due to NH_3 or RDP deficiency, manure CH_4 emission may also increase; this will not be the case if only manure N is decreased (due to dietary N reduction) without affecting rumen function or fermentable substrate availability in manure. Within limits, N *per se* does not seem to affect microbial fermentation and CH_4 production from manure, as has been demonstrated by Lee *et al.* (2012a).

In some production systems, ruminant diets are often already deficient in fermentable N (i.e. RDP), thus limiting rumen function during parts of the year (dry season) and animals may consume an excess of RDP during the wet season (Preston and Leng, 1984, 1986). In these conditions, nutrient balance in the rumen for maximizing microbial protein output and fibre degradability may be difficult to achieve. Strategic supplementation (see *Mitigation options for production systems based on low-quality feeds*) or better balancing dietary nutrients (see *Precision feeding and feed analyses*) when lush pasture is available are critical for maximizing animal productivity and minimizing enteric CH_4 emissions from livestock in developing countries.

Feed intake depression with protein- and AA-deficient diets has been demonstrated with pigs and poultry (Henry, 1985; Picard *et al.*, 1993) and must be avoided in order to maintain efficient production. Henry (1985) stated that feed intake and growth performance of pigs were depressed both by a severe deficiency in dietary limiting AA and by an excessive supply of total protein or some essential AA. Deficiencies of key AA may also increase urinary N losses, as shown in pigs by Brown and Cline (1974). Supplementation of low-protein diets with synthetic AA may alleviate undesirable effects on feed intake. Growing pigs fed a 14 percent CP diet containing supplemental lysine (0.73 percent lysine) resulted in intake and growth performance being similar to pigs fed a 16 percent protein diet (0.77 percent lysine) (Baker *et al.*, 1975). Analogous results were reported by Yen and Veum (1982) who observed feed intake and ADG with growing pigs fed a protein deficient (13 percent CP) diet supplemented with lysine and tryptophan to be similar to pigs fed a 16 percent CP diet.

Overfeeding of protein may also depress feed intake; there is sufficient evidence that elevated blood plasma concentrations of AA that cannot be used for protein synthesis depress feed intake in rats and monogastric farm species (Peng and Harper, 1970; Henry, 1985). Low-protein diets can decrease feed intake, milk production and milk protein concentration in dairy cows (Lee *et al.*, 2012b,c). Such effects will result in increased GHG emissions per unit of milk, thus offsetting the potential reduction in manure NH_3 and N_2O emissions due to decreased urinary N excretion.

Similar to monogastric animals, however, supplementation of the diet with rumen-protected AA (lysine, methinine, histidine) increased DMI and milk production in high-producing dairy cows (Lee *et al.*, 2012c). In some cases, extremely low dietary protein concentrations did not seem to affect milk production of dairy cows, although nutrient digestibility and microbial protein synthesis in the rumen were depressed (Aschemann *et al.*, 2012). These results, however, have to be interpreted in the context of level of milk production, experimental design (specifically trial duration) and MP supply relative to animal requirements.

The effects of MP- and AA-deficiency on milk production may not be manifested in short-term, i.e. cross-over design, experiments due to mobilization of body reserves by the cow. An example of this is the study by Lee *et al.* (2012c), which demonstrated histidine to be a limiting AA in high-producing dairy cows fed a MP-deficient diet. In that study, blood histidine concentrations were about 50 percent lower in the MP-deficient vs MP-adequate diet, and supplementation with rumen-protected histidine, in addition to lysine and methionine, eliminated the drop in milk production observed with the MP-deficient diet. In a parallel Latin square design study, however, milk production and plasma histidine concentrations were not affected by similar dietary MP-deficiency (Lee *et al.*, 2011c). In their analysis of these data, Lee *et al.* (2012c) pointed out that muscle depots of di-peptides (carnosine, anserine) may serve as sources of histidine (Lapierre *et al.*, 2008) and thus histidine deficiency may not become apparent in short-term experiments. In the study of (Aschemann *et al.*, 2012) in which dietary CP was as low as 12 percent, intake of the cows was restricted and the important effect of CP on DMI (Lee *et al.*, 2011a; Picard *et al.*, 1993) could not be demonstrated.

Overall, feeding protein close to animal requirements, including varying protein concentration with the productive stage of the animal, is recommended as an effective manure NH_3 and N_2O emission mitigation practice. Low-protein diets for ruminants should be balanced for RDP in order not to impair microbial protein synthesis and fibre degradability in the rumen. Diets for all animals should be balanced for AA to avoid feed intake depression and decreased productivity.

PENNSYLVANIA STATE UNIVERSITY, A.N. HRISTOV

photo 8
Free-stall type dairy in the western United States

Dietary manipulation

Feeding dairy cows low-protein diets dramatically reduces the proportion of urinary, particularly urinary urea N (more than 50 percent) in animal excreta (Misselbrook *et al.*, 2005a; Colmenero and Broderick, 2006) to around or below 19 percent in dairy cows fed diets supplying MP levels 15 percent below NRC (2001) requirements (Lee *et al.*, 2011a; Lee *et al.*, 2012b).

Other authors have shown that dietary CP reduction can reduce both CH_4 and N_2O emissions from stored manure (e.g. Atakora *et al.*, 2011a, 2011b ; Osada *et al.*, 2011) as well as following land application (Velthof *et al.* 2005). Land application reductions are not supported by all data because of the large variation in soil conditions. In intensively-managed pastoral systems, supplementation of the pasture with low-N feeds such as corn or small grain silage, which will generally reduce dietary N concentration, can reduce urinary N losses and consequently, manure and soil NH_3 and N_2O emissions (by 8 to 36 percent; de Klein and Monaghan, 2011). In some systems, however, this reduction may be of a smaller magnitude (Velthof *et al.*, 2009), or total GHG emissions may be even increased (Beukes *et al.*, 2010), perhaps due to increased synthetic fertilizer use to grow the cereal silage.

Diet manipulation or feed additives can also reduce GHG emissions from pig and poultry manure. Philippe *et al.* (2009) demonstrated that a high-fibre sow diet fed on a restricted basis could reduce both CH_4 and N_2O emissions from the building. Wu-Haan *et al.* (2007) found that zeolite addition to low protein laying hen diets could reduce manure CH_4 emission compared with manure from hens receiving untreated diets. The addition of thymol to sow diets reduced CH_4 emissions from sow manure by up to 93 percent (Varel and Wells, 2007). Similar to growing beef, phase-feeding allows swine and poultry producers to better match nutrients to the changing growth requirements and thus dramatically reduce manure nutrient excretions. Exogenous enzymes such as phytase not only enhance dramatically phytate-P utilization in monogastric animals but also improve the digestibility of protein and reduce N excretion in manure. Wet-dry feeders have been shown to increase efficiency by reducing the amount of feed required to achieve a desired weight gain (Pennsylvania State University Extension; http://extension.psu.edu/aec/factsheets/greenhouse-swine-and-poultry, accessed on 9 February 2013).

Nutrient efficiency can be sought in the field as well. Rochette *et al.* (2004), Sauer *et al.* (2009), Jarecki *et al.* (2009), and Meade *et al.* (2011) showed that applying N in balance with crop demands can lower N_2O emissions. Utilization of cover crops when fields lie fallow can hold N in forms that do not easily undergo denitrification (Sauer *et al.*, 2009).

> *In conclusion, decreased digestibility of dietary nutrients is expected to increase OM concentration in manure, which may increase manure CH_4 emission. Excess dietary protein should be avoided because this will likely increase manure N_2O emission following land application. Overfeeding of protein should also be avoided to reduce NH_3 emission from manure. Although not a GHG, NH_3 is considered an air pollutant contributing to water eutrophication, fine particulate matter ($PM_{2.5}$) formation and soil acidification. Ammonia can also provide an indirect source of GHG by transforming to N_2O following deposition.*

Housing

Structures used around the world to house livestock animals do not directly affect the processes resulting in N_2O and CH_4 emissions; however, the type of structure used to house animals determines the method used to store and process manure and eventual litter. Thus, housing design can have a significant indirect impact on NH_3 and CH_4 emissions from animal manure.

Housing systems with solid floors that use hay or straw for bedding accumulate manure that has higher DM and is commonly stored in piles creating conditions conducive for nitrification and denitrification resulting in higher N_2O emissions. Külling *et al.* (2001, 2003) compared liquid manure with stacked manure handling systems, and their results indicated that farm yard manure and deep litter manure handling systems tend to produce higher N_2O emissions than slurry-based systems. In these studies, quantitative differences in N_2O emissions from the manure handling systems being evaluated were difficult to determine because protein content in the diet and NH_3 emission from manure also varied. Higher CH_4 emissions were reported from farm yard manure, followed by liquid slurry and deep litter manure.

Amon *et al.* (2001) compared composted, anaerobically-stacked and slurry-based manure and found higher NH_3 emissions in composted manure with most of the losses occurring after manure was turned during aeration. These authors found much higher N_2O and CH_4 emissions from anaerobically-stacked manure and no significant difference between slurry-based and straw-based manure systems.

Housing systems with slatted floors accumulate manure in liquid form, which is commonly stored for longer periods of time and therefore tends to increase the production of CH_4 and reduce the production of N_2O.

Hassouna *et al.* (2010) studied gaseous emissions from cattle housing in France and found higher N_2O emissions in buildings with straw-based bedding and solid manure handling systems when compared with liquid manure handling systems. Nitrous oxide emissions were detected in only two of the 14 liquid manure systems studied by Hassouna *et al.* (2010). The same study found smaller differences between CH_4 emissions from buildings using straw-based solid manure or liquid manure systems and attributed this result to the difficulty in discerning enteric CH_4 emissions from emissions resulting from manure because the former comprise most of the CH_4 emitted from the buildings studied.

Hristov *et al.* (2012b) investigated the effect of manure management on barn floor NH_3, CH_4, N_2O, and CO_2 emissions from 12 commercial dairy farms in Pennsylvania. Dairies participating in the study had flush (manure was flushed twice daily), two types of scrape (manure was scraped daily) and gravity-flow (manure was accumulated under the building and removed several times during the year) manure systems. Barn floor NH_3 emissions were considerably lower for the flush manure systems (average of 167 mg/m^2/h) and highest for the gravity-flow system (426 mg/m^2/h). Methane emissions were also lowest for the flush (37 mg/m^2/h) and much higher for the gravity-flow system (1 216 mg/m^2/h). Carbon dioxide emissions were not different between manure systems (ranging from about 2 000 to 7 000 mg/m^2/h), and N_2O emissions were negligible in all systems. This study showed that NH_3, and particularly CH_4, emissions from manure are much higher from dairy barns in which manure is stored for prolonged periods of time than in barns from which manure is removed daily.

With ruminants, however, the animal is the main source of GHG and housing design and manure system within the animal housing usually have a smaller effect on CH_4 emissions, with N_2O emissions from manure storage being negligible. Jungbluth *et al.* (2001), for example, reported 223 g CH_4, 6.5 kg CO_2, and only 1.6 g N_2O emissions per livestock unit (1 livestock unit = 500 kg BW) per day from dairy cows in loose housing in Germany.

There is a large amount of research on the effect of housing on NH_3 emission from swine operations. The amount of manure stored in under-floor storage has no significant impact on NH_3 emissions. It is surface area of manure, not volume, which is proportional to NH_3 release (Ni *et al.*, 1999).

Continuous feeding of manure pits in commercial piggeries affects the air volume in the pit above the manure. This change may influence airflow patterns inside the pits. The type of floor in swine housing has some bearing on the NH_3 concentration in the air of the pig house. In swine houses with both solid (38 percent) and slatted floors (62 percent) above manure storage pits, approximately one-third of NH_3 emissions originated on the slatted floor and two-thirds from under-floor pits (i.e. 60-70 percent from pits; Hoeksma *et al.*, 1992). Another study reported that in pens with 25 percent and 50 percent slatted floors, 40 percent and 23 percent of NH_3 emissions originated from the slats, respectively (Aarnink *et al.*, 1996).

Surface area of dung in these buildings affects NH_3 emissions (Hesse, 1994; Aarnink *et al.*, 1996; Jungbluth and Büscher, 1996). Because floor contamination increases the surface area of manure, a positive linear relationship between steady state NH_3 emissions and area of floor contamination has been shown to exist (Hesse, 1994, Ni *et al.*, 1999). Higher floor contamination is related to weight of pigs and inside temperature (Hoeksma *et al.*, 1992; Ni *et al.*, 1999). Greater areas are befouled in summer than winter (Voermans and Hendriks, 1995). The influence of ventilation rate and inside air temperature on NH_3 release is stronger when floors have higher contamination rates (Ni *et al.*, 1999).

In most agricultural settings, manure surface area is influenced by animal activity, with a renewal of the surface layer of the manure on the floor or in the pit with excretion, urination or other physical disturbance. Philippe *et al.* (2007) compared GHG emissions from fattening pigs raised on concrete slatted floor or straw based deep litter. Pigs fattened on deep litter released nearly 20 percent more GHG than on slatted floor (6.2 and 13.1 g per pig per day for NH_3, 0.54 and 1.11 g per pig per day for N_2O, and 16.3 and 16.0 g per pig per day for CH_4, respectively).

The type of housing system also determines the feasibility of using anaerobic digestion or composting to treat the manure with its associated effects on non-CO_2 GHG emissions. As described in IAEA (2008), the types of housing system used in Asia facilitate different strategies for manure treatment depending on the capital resources of the producer. Housing systems used by small producers with limited capital resources usually have solid concrete floors and provide limited options for manure treatment. A popular alternative for smallholders is anaerobic digestion of animal and household waste, usually funded by government programmes. Medium to large producers have better access to capital investment, have specialized production determined by surrounding markets, and generally use raised slatted floors that allow collection of manure for further treatment through solids separation and anaerobic digestion.

Enclosed housing systems provide additional opportunities to mitigate N_2O and CH_4 emitted from manure and enteric fermentation inside the structure. Gases temporary collected inside mechanically ventilated structures in Europe and North America provide opportunities to treat those gases as they are evacuated via the exhaust stream through filtration and scrubbing as discussed in the previous section. An interesting mitigation technology uses titanium dioxide (TiO_2) paint on the interior wall of swine houses. Industrial uses of TiO_2 show that stimulation of its photocatalytic properties by UV light lead to oxidation of NH_3 and NOx (e.g. Lee *et al.*, 2002; Allen *et al.*, 2005). Studies by Guarino *et al.* (2008) and Costa *et al.* (2012) in swine houses showed that GHG mitigation with TiO_2 paint holds promise, but further research on practical implementation is warranted. Alkali and alkaline earth metal oxides, hydroxides and carbonates/bicarbonates have been shown to have high CO_2 absorption capacity and are being investigated for CO_2 sorbent applications (Duan *et al*., 2012). In the future, these technologies may find application as GHG mitigation options in animal agriculture as well.

> *Animal housing may affect GHG emissions through the method used to collect, store and process manure and litter. Farm yard manure and deep litter manure handling systems tend to produce higher N_2O emissions than slurry-based systems. Straw-based bedding and solid manure handling systems also tend to increase N_2O emissions compared with liquid manure handling systems. 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. Slatted floor manure systems tend to decrease GHG and NH_3 emissions compared with deep litter systems. In general, the effect of housing for ruminant animal on CH_4 emissions is relatively small because the animal is the main source of CH_4; N_2O emissions from ruminant housing are also usually negligible. However, housing and manure systems have a greater impact on NH_3 emission from animal operations.*

Biofiltration

This technology is based on treatment of ventilated air from animal buildings using biological scrubbers to convert NH_3 into NO_3, or biological beds to absorb NH_3. It has also been used for odour control. Preventing NH_3 losses may also indirectly reduce N_2O emissions by reducing ammonium deposition and consequent conversion to N_2O (see earlier discussion).

PENNSYLVANIA STATE UNIVERSITY, A.N. HRISTOV

photo 9

Free-stall type dairy in the eastern United States

Note: In this type of housing, 25 percent of N input as feed was not accounted for in milk and manure in a 24-hour period (Hristov *et al.*, 2011a).

Ammonia removal efficiency in swine and poultry houses from acid scrubbers and biotrickling filters (based on biofilms that degrade the odorous compounds) averaged 96 percent and 70 percent, respectively (Melse and Ogink, 2005). Shah *et al.* (2011) investigated the effectiveness of a coupled biofilter-heat exchanger in reducing NH_3 emissions (and recover heat) in a broiler house. The biofilter was effective in treating very high inlet NH_3 concentrations (> 96 mg/kg) with removal efficiencies > 79 percent for empty bed residence times ranging from 4.3 to 29.1 seconds. The biofilter was apparently also able to trap some sulphurous gases emitted from the broiler house.

Recent reports (Maia *et al.* 2012a, 2012b) have shown that biofilters used to scrub NH_3 from exhaust streams in animal houses generate N_2O as a result of nitrification and denitrification processes in the biofiltration media. In their first study, Maia *et al.* (2012a) showed a high correlation between biofilter NH_3 removal and N_2O generation associated with conversion of NH_3 to nitrite and nitrate in the biofilter. In their second study, Maia *et al.* (2012b) reported that moisture content between 48 to 52 percent in the biofilter media was an important factor in obtaining significant NH_3 reduction and reducing N_2O production. Thus, N_2O production in biofilter scrubbers should be taken into account when implementing biofiltration systems for GHG and NH_3 mitigation.

A few studies have investigated CH_4 mitigation by passing contaminated air from above a swine manure storage or from swine housing through a biofiltration system. A Canadian Pork Council (2006) study reported reductions of 50 to 60 percent, and Girard *et al.* (2011) reported a maximum reduction of up to 40 percent. Girard *et al.* (2011) described their biofilter as "packed with inorganic material", but the nature of the packing material was not disclosed.

Melse and Van der Werf (2005) reported up to 85 percent CH_4 removal from the exhaust stream of a covered swine liquid manure storage using a biofiltration system composed of a mixture of compost and perlite inoculated with CH_4 oxidizing bacteria collected from activated sludge. The CH_4 removal capacity of the biofilter system tested in that study depended on the concentration of CH_4 in the filtered stream and, therefore, the authors extrapolated that an equivalent system for animal housing with low CH_4 concentration in the filtered stream would require very large biofilter systems to achieve 50 percent reduction or more, pointing to this as a limitation in the applicability of this approach. In addition, they reported N_2O production in the biofiltration system contributing from 4 to 64 percent of the outlet stream GHG-CO_2 equivalents, which as mentioned above, needs to be included in the design and promotion of biofiltration strategies for GHG mitigation.

High residence time is necessary in these systems because the low solubility and biodegradability of CH_4 hinder effectiveness (Melse and Verdoes, 2005). Melse and Timmerman (2009) reported on the potential to use multi-pollutant scrubbers, combining acid scrubbers, biological filters and water curtains to reduce not only NH_3, odours and GHG but also particulate matter from animal housing exhaust systems.

Provided there is sufficient air residence time, biofilters can be recommended as an abatement strategy for CH_4 (as well as NH_3 and odour) but may not be applicable for many animal operations. Potential N_2O production in biofilter scrubbers should be taken into consideration.

Manure storage and separation

Greenhouse gas emissions from stored manure are primarily in the form of CH_4 (due to anaerobic conditions). Volatilization losses of NH_3 are large and N_2O emissions could also occur. One simple way to avoid cumulative GHG emissions is to reduce the time manure is stored (Philippe *et al.*, 2007; Costa *et al.*, 2012). Increasing the time of manure storage increases the period during which CH_4 (and potentially N_2O) is emitted, as well as the emission rate, creating a compound effect (Philippe *et al.*, 2007).

Storage treatments that provide aeration such as mechanical aeration[27] or intermittent aeration[28] have been shown to reduce CH_4 emissions. Temperature is a critical factor regulating processes leading to NH_3 (Sommer *et al.,* 2006) and CH_4 (Steed and Hashimoto, 1994) emissions from stored manure. Decreasing manure temperature to < 10 °C, by removing the manure from the building and storing it outside in cold climates, can mitigate CH_4 emissions (Monteny *et al.*, 2006).

Philippe *et al.* (2007) demonstrated that fattening pigs raised on slatted floors yielded less non-CO_2 GHG emissions than those reared in deep litter (N_2O, $P < 0.001$; CH_4 lower but not statistically significant), although the values reported in the literature for these systems are highly variable. Recently, Dong *et al.* (2011) studied stacking of raw manure of Chinese hogs in a laboratory setting. Relationships between stacking height and both CH_4 and N_2O emissions were found, and a stack height of 20 cm mitigated both gases.

Proper aeration and moisture management have reduced CH_4 generation from poultry manure (Li and Xin, 2010). Ventilated belt removal of laying hen manure can reduce CH_4 emissions compared to deep-pit storage (Fabbri *et al.*, 2007). A wide range of storage management and treatment scenarios exist, and more work is needed to develop practical and economically feasible techniques that can be widely used.

Separation of swine slurry into solid and liquid portions, and then treating the solids through aerated composting reduced CH_4 emissions by 99 percent and N_2O emissions by 75 percent

---

[27] See Martinez *et al.* (2003); Boursier *et al.* (2004); Amon *et al.* (2006); and Loyon *et al.* (2007).

[28] See Osada (2000); and Osada *et al.* (1995).

compared with untreated manure (Vanotti *et al.*, 2008). However, due to the often negative relationship between NH_3 and N_2O emissions (Petersen and Sommer, 2011), this process is likely to increase NH_3 emissions and perhaps total N losses from manure. Amon *et al.* (2001) reported higher NH_3 losses from an actively turned composting pile of solid cattle manure than from an undisturbed anaerobically stored pile, with the opposite effect for N_2O emissions.

As pointed out by Petersen and Sommer (2011), in manure management, all GHG emissions and energy transformations must be considered. Sommer *et al.* (2009) simulated several manure management scenarios using data from four European countries and suggested that solids and liquid separation followed by incineration of the solids can reduce overall GHG emissions by 49 to as much as 82 percent compared with the reference system. Cayuela *et al.* (2010) investigated C and N dynamics and GHG emissions following application of 10 by-products from different bioenergy processes (anaerobic digestion, first and second generation biofuel by-products, rapeseed meal, DDGS, different lignocellulosic materials, and pyrolysis, i.e. biochars) to soil. After 60 days, over 80 percent of applied C was emitted as CO_2 in the first-generation biofuel residue treatments, 60 percent for the second-generation biofuel residues, and 40 percent for the anaerobic digestion residues. Biochars had the lowest CO_2 loss (between 0.5 percent and 5.8 percent of total added C). First-generation biofuel residues resulted in the highest total N_2O emissions (between 2.5 percent and 6.0 percent of applied N), followed by second-generation biofuel residues (1.0 percent to 2.0 percent of applied N), anaerobic digestion residues (less than 1 percent of applied N), and the biochars decreased N_2O emissions below background values.

> *Most mitigation options for GHG emissions from stored manure, such as reducing the time of manure storage, aeration, slatted floors and stacking, are generally aimed at decreasing the time allowed for microbial fermentation processes to occur or at creating aerobic conditions before land application. These mitigation practices are effective, but their economic feasibility is uncertain. Separation of manure into liquid and solids and aerobically composting the solids has been shown to reduce* CH_4 *but may have a variable effect on* N_2O *emissions and will increase* NH_3 *and total manure N losses.*

Manure storage covers

Several types of manure storage covers have been reported in the literature, ranging from natural crusts in manure storages with high solids content[29], to straw, wood chips, oil layers, expanded clay, wood, semi-permeable and sealed plastic covers[30]. The effectiveness of the manure storage cover depends on many factors, including permeability, cover thickness, degradability, porosity and management. Semi-permeable covers such as naturally crusted manures, straw, wood chips and expanded clay generally reduce odour and NH_3 and CH_4 emissions, with the level of reduction depending on the permeability and thickness of the cover layer[31].

---

[29] See Misselbrook et al. (2005b); and Smith et al. (2007b).

[30] See Sommer *et al.* (2000); Nicolai and Pohl (2004); Bicudo *et al.* (2004); Clemens *et al.* (2006); Guarino *et al.* (2006); and VanderZaag *et al.* (2008, 2009, 2010).

[31] See Sommer *et al.* (2000); Lague *et al.* (2005); Guarino *et al.* (2006); Clemens *et al.* (2006); and VanderZaag *et al.* (2008).

Nonetheless, semi-permeable storage covers tend to increase N_2O emission because they provide optimal aerobic conditions for nitrification at the cover surface and at the same time create a low oxygen environment just below the cover favourable for denitrification and production of N_2O (Hansen *et al.*, 2009; Nielsen *et al.*, 2010). Semi-permeable covers are valuable for reducing NH_3, CH_4, and odour emissions but likely increase N_2O emissions (Sommer *et al.*, 2000; Guarino *et al.*, 2006; VanderZaag *et al.*, 2008). Therefore the effectiveness of semi-permeable manure storage covers is not clear, and results vary widely depending on the material and the particular conditions in which it is applied.

Capturing the gases produced using impermeable membranes, such as oil layers and sealed plastic covers, would result in reduced NH_3, N_2O and CH_4 emissions[32]. The results from Guarino *et al*. (2006) and VandeerZaag *et al.* (2008) suggest that using a vegetable oil layer as a manure storage cover, although very effective, is not very practical because of degradability, generation of foul odours and difficulty in preventing the oil film from becoming mixed or "broken" over the manure surface.

Covering manure storages with impermeable covers is an effective mitigation practice if the CH_4 captured under the cover is burned using a flare system or engine-generator to produce electricity; otherwise the captured CH_4 would build pressure inside the storage creating an explosion hazard and/or escape through leaks and cover ruptures. Sealing the manure storage with an impermeable cover results in increased air pressure inside the storage structure reducing the fraction of gases in the gas phase and increasing the fraction trapped in liquid manure. The increased fraction of gases trapped in the liquid fraction of the manure is then released when the pressure in the manure storage container is reduced as manure is transported and applied in the field.

Retaining the CH_4 produced is not beneficial if it escapes at a later stage; therefore, burning or combusting the collected CH_4 to produce electricity or heat is the most desirable option. The effectiveness of impermeable covers depends on transforming the collected gases to less potent GHG gases such as NOx and CO_2 (Nicolai and Pohl, 2004; Rotz and Hafner, 2011).

Semi-permeable covers are valuable for reducing NH_3, CH_4 and odour emissions but likely increase N_2O emissions; therefore, their effectiveness is not clear and results may vary widely. Impermeable membranes, such as oil layers and sealed plastic covers, are effective in reducing gaseous emissions but are not very practical. Combusting CH_4 accumulated under impermeable covers to produce electricity or heat is recommended.

Manure acidification

An important factor affecting GHG emissions, in particular NH_3, from stored manure is pH. 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. The relationships between NH_3 volatilization and factors such as air velocity and turbulence, manure temperature and manure pH have been well-documented (see discussion in Ndegwa *et al.*, 2011).

---

[32] See Nicolai and Pohl (2004); Bicudo *et al.* (2004); Guarino *et al.* (2006); and VanderZaag *et al.* (2008).

Ammonia volatilization is directly proportional to the proportion of NH_3-N in the total ammoniacal nitrogen (TAN) in manure. At constant temperature, the dissociation constant (Kd), which is a function of medium pH, determines the equilibrium between ammonium and NH_3 in aqueous systems. Lower manure pH results in lower proportion of NH_3 and, therefore, decreased potential of NH_3 volatilization. Acidification of animal manure for mitigation of NH_3 emission relies on this fundamental principle.

Ndegwa *et al.* (2011) listed 15 studies in which cattle, pig or poultry manure NH_3 emissions were successfully mitigated (from 14 to 100 percent reduction in emissions) by lowering manure pH with sulphuric, hydrochloric or phosphoric acids, calcium chloride, alum or monocalcium phosphate monohydrate. These authors concluded that strong acids are more cost-effective at reducing manure pH than weaker acids or acidifying salts. However, strong acids are more hazardous and, therefore, acidifying salts and weaker acids may be more suitable for on-farm use. Acidification of urine and, consequently, manure from cattle or mono-gastric farm animals has been also attempted using anionic salts, high dietary levels of fermentable carbohydrates, organic (benzoic) acids, or Ca- and P-salts (see discussion in Ndegwa *et al.*, 2008).

A commercial system used on several farms in Denmark acidifies a portion of the manure with concentrated sulphuric acid to a pH of 5.5, removes a portion of the acidified manure equivalent to the daily manure production, and returns the remaining manure to the storage facility (Sørensen and Eriksen, 2009). These authors concluded that NH_3 volatilization from acidified cattle and pig manure was low, after both soil incorporation and surface application. Petersen *et al.* (2012) studied the effect of acidification on CH_4 (and NH_3) emission from fresh and aged cattle manure during three months of storage. Manure pH was adjusted to 5.5 with sulphuric acid. The commercial equipment described above was also studied on two farms. Samples of manure were stored for 95 days, and NH_3 and CH_4 emissions were monitored. Manure pH increased gradually to 6.5 to 7 during storage. Acidification had a dramatic effect on emissions, reducing CH_4 by 67 to 87 percent (more pronounced with aged manure) and almost completely eliminating NH_3 emissions. The authors concluded that manure acidification may be a cost-effective GHG mitigation practice.

Application of acidified manure is not expected to greatly impact crop production; the pH range of acidified manure is within the optimal range for corn and many cereal crops (5.5 to 6.5; Tisdale *et al.*, 1993). Approximately 30 percent of soils worldwide, and about 60 percent in Asia, are acidic (< pH 5.5) and already require periodic lime applications to maintain optimal pH (von Uexküll and Mutert, 1995). Smaller quantities of acidified manure would also be needed per hectare to provide crop N requirements because the reduction in NH_3 emissions provides manure with a greater plant-available N content. However, long-term impacts of the land application of acidified manures on soil pH have not been reported, and more frequent application of lime to maintain optimal pH in some soils could be required. Application of acidified manure onto acidified soils could exacerbate this problem.

Moderate decrease in manure pH through acidification significantly reduces NH_3 volatilization and CH_4 losses from stored manure. The effect on N_2O emissions following soil application is not well studied and may be increased if the inverse relationship between NH_3 and N_2O emissions holds in this case.

Composting

Composting is an exotermic, aerobic process of microbial decomposition of organic matter that has several benefits related to manure handling, odour control, manure moisture and pathogen control, OM stabilization, additional farm income, etc. Composted manure solids (following manure separation into solids and liquid) is also being used as bedding in some dairy production systems to reduce cost of production and provide cow comfort, assuming udder health is not compromised (Husfeldt *et al.*, 2012).

However, due to the nature of the composting process, N losses can be high and are influenced by a number of factors, including temperature, C/N ratio, pH, moisture and material consistency (Zeman *et al.*, 2002). Compost can be a source of N_2O emissions. Both nitrification and denitrification processes occur in composted manure, with *Bacillus* species being the main players in the degradation of organic material and betaproteobacterial NH_3-oxidizing bacteria involved in the nitrification process (Maeda *et al.*, 2011). Hao *et al.* (2004) reported up to 30 percent DM, 53 percent C, and 42 percent of the initial N being lost during composting of straw-bedded manure. Methane losses accounted for 6 percent of the C losses, but the net contribution of CH_4 to total GHG losses was the highest. Nitrous oxide losses represented 1 to 6 percent of the total N losses.

Depending on the intensity of composting, NH_3 losses can be particularly high, reaching up to 50 percent of the total manure N (Peigné and Girardin, 2004). Aeration of composting heap 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).

Addition of mature compost with nitrite-oxidizing bacteria to actively composted swine manure was shown to reduce N_2O emission by 70 percent (Fukumoto and Inubushi, 2009). These authors reported that up to 19 percent of the total manure N was lost as NH_3 and N_2O. Brown *et al.* (2008) reviewed the impact of composting of a range of feed stocks (including animal manure) on GHG emissions.

As discussed earlier and pointed out by Brown *et al.* (2008), the primary benefit of composting is that it reduces CH_4 emissions compared with storage of manure under anaerobic conditions. These authors estimated, for example, that a facility that composts an equal mixture of manure, newsprint and food waste could conserve the equivalent of 3.1 Mg CO_2 per Mg of dry feed stocks composted if feed stocks were diverted from anaerobic storage lagoons and landfills with no gas collection mechanisms. Greenhouse gas debits are accumulated through the energy required for the composting process and the release of GHG during composting.

According to Clemens *et al.* (2006), raw cattle manure can release from about 160 (winter) to 3 600 (summer) g/m^3 CH_4 and 38 to 57 g/m^3 N_2O. For digested manure, the release rates are from 80 (winter) to 1 200 g/m^3 (summer) CH_4 and 40 to 76 g/m^3 N_2O respectively. A recent study by Kariyapperuma *et al.* (2012) reported a 57 percent decrease in soil N_2O emissions with composted vs liquid pig manure. Remarkably, emissions during the same period of the following year were not different between composted and non-composted manure; the authors attributed the lack of difference to a significant reduction in emissions in the second year due to freezing of the soil.

In spite of significant GHG emissions from composting, however, the review by Brown *et al.* (2008) concluded that, even in a worst-case scenario, these emissions are minimal in comparison to the benefits associated with the CH_4 reduction credits from composting. The authors also stated that it is possible to significantly reduce emissions from compost piles by increasing the solids content of the feed stocks and the C/N ratio. Overall, Brown *et al.* (2008) concluded that composting can be an effective method for reducing GHG emissions from a range of waste materials, including animal manure. It must be noted, however, that NH_3 losses during manure composting are significant.

Aerating, reducing moisture and increasing solids content of stored manure are some of the practices that reportedly prevent anaerobic conditions during manure storage and therefore reduce CH_4 emissions[33]. When manure is stored as a liquid or slurry, it is difficult to avoid anaerobic conditions, so the most effective practice is to cover the storage to prevent CH_4 emissions.

> *Composting of animal manure causes significant N and CO_2 losses, but the benefits of reducing odour and CH_4 emissions, compared with anaerobically-stored manure, make it a recommended GHG mitigating option. Nitrogen losses, predominantly as NH_3 but also as N_2O, however, are large.*

Anaerobic digestion

Anaerobic digestion is the process of degradation of organic materials by archaea in the absence of oxygen, producing CH_4, CO_2, and other gases as by-products and is a promising practice for mitigating GHG emissions from collected manure. In addition, when correctly operated, anaerobic digesters are a source of renewable energy in the form of biogas, which is 60 to 80 percent CH_4, depending on the substrate and operation conditions (Roos *et al.*, 2004). Anaerobic digesters also provide opportunities to reduce pathogens and manure odour[34].

During the anaerobic digestion process, N-containing compounds found in substrates, such as proteins, AA and urea, are reduced to NH_3 (Bernet *et al.*, 2000). Ammonia remaining in the aqueous solution is used for crop fertilization when the digestate is land-applied (Bernet *et al.,* 2000; Hafner *et al*., 2006). Anaerobic digestion stabilizes the organic C in the feedstock (reducing the fraction of easily degradable C in manures), increases plant availability of N and provides less energy to support the growth of N_2O-forming microorganisms, reducing the potential of N_2O emissions when applied to soil[35]. Mineralization of organic N and VFA during anaerobic digestion increases manure pH and available N, which may potentially increase NH_3 volatilization (Petersen and Sommer, 2011).

In general, reduction of manure OM content is expected to reduce N_2O emissions from manure-amended soils (Petersen, 1999; Bertora *et al.,* 2008), although Thomsen *et al.* (2010) reported higher N_2O emissions when treated manure[36] was applied in a wet spring. These contradictory results led Petersen and Sommer (2011) to conclude that there is no simple relationship between removal of manure OM and the risk of N_2O emissions. To address this controversy, Thomsen *et al*. (2010) proposed linking the balance between N_2O and N_2 to soil water-filled pore space and O_2 supply. This relationship has been discussed in detail by Petersen and Sommer (2011); the authors concluded that prediction of N_2O

---

[33] See Amon *et al.* (2001); Cardenas *et al.* (2007); Moller *et al.* (2004); and Molodovskaya *et al.* (2008).

[34] See Abou Nohra *et al.* (2003); Remais *et al.* (2009); and Dhingra *et al.* (2011).

[35] See Safley and Westerman (1994); Petersen (1999); Sommer *et al.* (2000); and Lantz *et al.* (2007).

[36] Using various treatment methods, including anaerobic digestion.

emissions from manure-amended soil depends on manure composition and soil conditions. Masse *et al.* (2011) noted high variability between N_2O emissions, referring to six studies[37] that found similar differences in emissions of the gas when comparing digested and non-digested manures. Three practical temperature ranges are generally considered for anaerobic biogas systems: psychrophilic (15 to 25 °C), mesophilic (30 to 38 °C), and thermophilic (50 to 60 °C). These temperature ranges facilitate the growth of specific microbes. Thermophilic systems are more sensitive to environmental changes, such as temperature fluctuations and chemical concentrations produced during the digestion process (Kim *et al.*, 2002; Ahn and Forster, 2002; El-Mashad *et al.*, 2003) because the number of functional microorganism species that thrive at this temperature is considerably less than those that survive at lower temperatures (Ziekus, 1977; Wolfe, 1979; Smith, 1980). Below 15 °C, the production of biogas is greatly reduced and CO_2 becomes the dominant product of anaerobic digestion; therefore, anaerobic digestion systems are not recommended for geographic locations with average temperatures below this threshold without supplemental heat and temperature control (Sommer *et al.*, 2007).

The effluent coming out of the digester, commonly called digestate, contains most of the soluble plant nutrients found in the feedstock and the more resilient, difficult to degrade organic material[38]. The digestate is commonly applied directly to crops while the sludge, formed by precipitated minerals and undigested OM, may be composted before being field-applied.

Digester designs vary widely in size, function and operational parameters. Smaller digesters (6 to 10 m^3) designed to improve sanitary conditions in developing countries and to provide energy for single family dwellings were promoted in the 1970s and 1980s throughout Asia and Latin America (Bond and Templeton, 2011; Jiang *et al.*, 2011a). These were designed to function with the waste originating from a few animals (two to five pigs, five to ten cows, 100 chickens, or a combination of these) together with the family dwelling waste.

According to Dhingra *et al.* (2011), these types of digester reduce GHG emissions between 23 percent and 53 percent when compared with households without biogas, depending on the condition of the digester, technical assistance and operator ability. The effectiveness of these types of digester for mitigating GHG depends mostly on the amount of CH_4 leakage[39] that occurs through digester walls and piping delivering biogas to the family dwelling (Dhingra *et al.*, 2011). These small digesters have been used by farmers in developing countries only when government subsidies and economic incentives have been available (Bond and Templeton, 2011).

Commercial farm digesters are typically designed to treat liquid manures. This is favourable for offsetting CH_4 emissions because liquid systems contribute to CH_4 emissions while manure stored in solid form produces little CH_4 (EPA, 2011). There are four basic commercial farm-level anaerobic digestion vessel designs (Roos *et al.*, 2004):

- *Covered lagoon digestion systems* are ambient (psychrophilic) temperature systems that require manure with a solid content of 3 percent or less and storage cover

---

[37] Pain *et al.* (1990); Rubaek *et al.* (1996); Velthof *et al.* (2005); Clemens *et al.* (2006); Vallejo *et al.* (2006); and Thomsen *et al.* (2010).

[38] See Shih (1987, 1993); Sundradjat (1990); Vermeulen *et al.* (1992); Salminen *et al.* (2001); and Lantz *et al.* (2007).

[39] This leakage increases GHG emission by 17 to 40 percent.

to maintain anaerobic conditions. These systems typically use the largest type of digester with the longest hydraulic retention time.

- *Complete mix digesters* consist of an engineered digestion vessel designed to handle manure slurries with a solid content from 3 to 10 percent. A mixing system enhances bacterial contact with OM. Supplemental heat is often added to these systems so that they operate at mesophilic temperatures, which promotes bacterial growth and a shorter hydraulic retention time.
- *Plug-flow digesters* and fixed domes use a vessel that receives manure at one end and discharges from the opposite end with no mixing or agitation. These systems may be heated to a mesophilic temperature and require slurry with a solid content of 11 to 13 percent. Small-scale digesters are often of this design.
- *Fixed-film digesters* use a medium, such as rope, plastic mesh or beads, placed in the vessel, on which bacteria can grow. Dilute manures with solid content of 3 percent or less are passed across (or through) the medium in these systems. While other systems rely solely on suspended microbial growth, these systems also feature attached microbial growth.

Widespread commercial farm digester adoption has not occurred because of variable economic return (Hill *et al.*, 1985; Safley and Westerman, 1994; Braber, 1995) and also because of the limited competitiveness of biogas with other fuel used for heat or combined heat and power (Lantz *et al.*, 2007)

Industrial biogas digesters are used to produce renewable energy for towns and municipalities. These digesters, prevalent mostly in Europe, use biomass collected from several farms to feed the anaerobic digesters. Co-digestion of agricultural biomass, industrial organic waste and animal manures is a common practice in industrial biogas plants because it allows the operator to optimize CH_4 production, while reducing the impact of ammonium on gas production and the C:N ratio to be optimized (Ward *et al.*, 2008).

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). These authors compared the emissions from the life cycle of raw materials used for anaerobic digestion (six various feed stocks, including swine manure) and the emission from systems that the anaerobic digestion process replaced. One of the serious concerns identified in the report involved uncontrolled losses of CH_4 from biogas plants, including losses from stored manure after it had been removed from gas collection areas and gas leakages in other system components. Typical losses from systems storing digested manure were reported to range from 5 to 20 percent of total biogas produced (Bjurling and Svärd, 1998; Sommer *et al.*, 2001).

In a follow-up report, Börjesson and Berglund (2007) further explored overall environmental impact when biogas systems replace various energy production reference systems. The investigation was based on Swedish conditions using an LCA approach while considering both direct and indirect effects between different biogas and reference systems. Greenhouse gas emissions per unit of heat were reduced 10 to 25 percent when biogas-based heat replaced fossil fuel-based heat. Emissions from biogas systems contributed 60 to 75 percent and 25 to 40 percent of the life-cycle emissions for CO_2 and CH_4 in the reference, fuel-based system, respectively.

Data on the anaerobic digestion of poultry waste as a GHG mitigation practice is very limited. Several studies show successful biogas production using poultry waste as a component of co-digestion (digesting poultry waste with other manures – beneficial due to the complementary composition of the different manures); however, the impact on GHG mitigation is not reported. The ability to use anaerobic digestion to create, capture and destroy CH_4 derived from swine manure is well documented (Safley and Westerman, 1994; Masse *et al.*, 2003a,b). Although it is possible to reduce CH_4 emissions by over 60 percent from swine manure using anaerobic digestion, the amount of CH_4 produced and collected does not directly translate into an equal amount of reduced CH_4 emissions because the untreated manure would have been unlikely to yield the same amount of CH_4 gas.

Most literature reviewed focused on research that compared digested manure with manures that received no treatment or a different treatment. In this manner, the biogas removed is not considered in the emission comparisons of non-digested versus digested manure by many authors who use the assumption that biogas produced during digestion will be destroyed through controlled combustion. A number of the studies referenced here considered emissions from digested manure after it was land-applied[40]. Reductions of N_2O emissions in these papers were as high as 70 percent compared with untreated manure applications. One commonly stated reason for this decrease was that digested manure contains less OM (degradable C) providing less energy for nitrite-forming microorganisms, which subsequently limits N_2O production.

Anaerobic digestion has a significant potential to capture and destroy most CH_4 from manure, but also because of its potential to avoid emissions of the gas from untreated manure and to provide energy and sanitation opportunities for developing countries. Although most anaerobic digestion systems significantly reduce GHG emissions when compared with traditional manure handling systems, incorrect operation, lack of maintenance and CH_4 leaks can make them a net contributor to GHG. For this reason it is imperative that system designs and components ensure containment of all biogas. The potential for anaerobic digestion to mitigate N_2O emissions after the digested manure is land applied is promising, but many parameters involved with field application have contributed to conflicting reports.

Anaerobic digestion systems require large initial capital investments during construction along with ongoing maintenance and supervision. Therefore, historically, the adoption of this type of technology occurs only when economic incentives are offered as price advantages for biogas (biofuels and renewable policy incentives), when the capital cost of construction and maintenance is subsidized or when no competitive energy source alternative is available. Furthermore, instruction and technical assistance to users are necessary in implementing successful anaerobic digestion mitigation practices because the correct operation of anaerobic digesters is not trivial and 50 percent failure rates are common (Bond and Templeton, 2011; Jiang *et al.,* 2011b).

Use of anaerobic manure digesters is a recommended GHG mitigation strategy that has a significant potential to capture and destroy most CH_4 from manure, generates renewable

---

[40] See Petersen (1999); Clemens and Huschka (2001); Amon *et al.* (2006); Monteny *et al.* (2006); Chantigny *et al.* (2007); Bertora *et al.* (2008); Insam and Wett (2008); and Pelletier *et al.* (2010).

energy and provides sanitation opportunities in developing countries. Management of digestion systems is important, so that they do not become net emitters of CH_4. There might also be a potential for mitigating N_2O emissions following land application of the digested manure, although results are contradictory. On larger farms, these systems may require large initial capital investments. The adoption of this type of technology on farms of all sizes may not be widely applicable and will heavily depend on climatic conditions and availability of alternative sources of energy. Instruction and technical assistance are also necessary in implementing successful anaerobic digestion mitigation practices. Anaerobic digestion systems are not recommended for geographic locations with average temperatures below 15 °C without supplemental heat and temperature control.

Manure application

As discussed earlier, manure is a valuable resource and is best utilized as fertilizer. However, increased animal density accompanied by continuous inflow of nutrients with imported feeds can lead to nutrient imbalance at a watershed scale and to water and air pollution due to manure application on soil. This kind of nutrient imbalance is more likely to occur in intensive animal production systems.

When input of recoverable manure nutrients (the quantity of manure nutrients that would be available for land application or utilization for other purposes) grossly exceeds the assimilative capacity of soil (the amount of nutrients that could be applied to land available for manure application without increasing nutrient levels in the soil over time), nutrient build-ups occur (Saam *et al.*, 2005).

Lander *et al.* (1998) categorized the ratio of recoverable manure to the assimilative capacity of cropland and pastureland at a county level from 1.0 (indicating that the county has county-level excess nutrients) to < 0.25 (indicating that less than 25 percent of nutrients taken up and removed by crops or applied to pasture could be supplied from manure generated within the county).

According to the US Department of Agriculture (USDA, 2000), the number of counties in the United States in 1997 with ratios of 0.5 or greater (i.e. surplus of nutrients) totalled 165 for N and 374 for P. Apparently, manure application in such regions is problematic, despite benefits to soil structure and fertility. For example, over the period 1987 to 2007 in the Mid-Atlantic region of the United States, N inputs with animal manure and fertilizer averaged 562 million kg/yr, while N outputs in harvested crops averaged 329 million kg/yr[41]. Maguire *et al.* (2007) estimated that in 89 percent of counties in the United States, there was a deficit of manure P relative to crop P removal and there was a manure P surplus in 11 percent of counties.

Therefore, in some regions, manure application can be limited by soil accumulation of nutrients. Surplus of nutrients can be a significant environmental problem for large livestock operations. For example, Hristov *et al.* (2006) reported average efficiency of use of imported N and P (total exports ÷ total imports × 100) on commercial dairy farms in Idaho (average size of 2 100 cows and 186 ha arable land) of 41 and 66 percent, respectively. Accumulation of nutrients was occurring on these dairies and as a result, soil P levels in the

---

[41] Source: Mid-Atlantic Water Program; available at http://www.mawaterquality.agecon.vt.edu/index.php.

30-cm layer were well above state threshold standards, most likely from over-application of manure. Soil nitrate-N was > 40 mg/kg for five of the eight dairies, and two were over 80 mg/kg. Such high N concentrations exceed the crop needs for optimal growth and represent an environmental concern.

When nutrient surplus is not an issue, manure is a valuable source of available nutrients for crops, successfully replacing artificial fertilizer. Soil N_2O emissions from application of inorganic N fertilizer can be significant. In an LCA analysis, Adom *et al.* (2012) found that N fertilizer input was the largest contributor to GHG emissions for feeds used by the dairy industry in the United States; about 65 percent due to N_2O release upon application and 35 percent from fertilizer manufacture. These authors recommended that farmers should be educated in fertilizer best management practices in order to effectively reduce GHG emissions on the farm.

An IPCC (2006b) report assumed N_2O emission factors (Tier 1) for mineral fertilizers and cattle, poultry and pig manure at 1 and 2 percent of N input, respectively. Soil N_2O emissions can vary greatly, and emission factors of up to 12 percent of N input (for nitrate-based fertilizer) and 5 percent for manure have been reported (de Klein *et al.*, 2001). Petersen (1999) reported no difference in soil emissions (in both cases below 1 percent of N input) between synthetic fertilizer (calcium ammonium nitrate) and a mix of cattle and pig manure. Similarly, Li *et al.* (2002) observed no differences in soil N_2O emissions between cattle manure and ammonium sulphate fertilizer applied at 150 or 300 kg N/ha.

One important difference between mineral fertilizer and manure is that manure contains organic C which, depending on soil conditions, may affect N_2O emissions. Manure C may increase microbial respiration rates in soil, thus depleting oxygen and providing the anaerobic conditions required for denitrification (Pelster *et al.*, 2012). As a result, organic amendments containing large amounts of labile C and available N (cattle, swine or poultry manure) have been reported to increase soil N_2O emission compared with mineral fertilizers[42].

However, this does not always appear to be the case because some studies reported greater N_2O emissions from soils fertilized with ammonium nitrate (Chantigny *et al.*, 2010) or urea (Lopez-Fernandez *et al.*, 2007) compared with manure-amended soils. Thus, Pelster *et al.* (2012) reported that the N_2O emission factor for plots amended with poultry manure was 1.8 percent, more than double that of the other treatments, including mineral fertilizer (0.3 to 0.9 percent), a result attributed to the high C content of poultry manure. These authors concluded that, compared with mineral N sources, manure application increases soil N_2O flux in soils with low C content.

Land application of poultry litter presents an opportunity to improve soil productivity and disposal of poultry waste. A study by Nyakatawa *et al.* (2011) investigated CH_4 and N_2O emissions from soil receiving poultry litter and ammonium nitrate using surface, soil incorporation and subsurface band application methods in conventional and no-tillage systems on a Decatur silt loam soil in North Alabama. Plots receiving ammonium nitrate were net emitters of CH_4 and N_2O, whereas plots receiving poultry manure were net sinks of CH_4. Nitrous oxide emissions from manure-amended soil depended on application method: surface or soil incorporation resulted in net emission of N_2O while manure-amended plots under subsurface band application were net sinks of N_2O.

---

[42] See Velthof *et al.* (2003); van Groenigen *et al.* (2004); Dong *et al.* (2005); and Gregorich *et al.* (2005).

However, another study with poultry manure did not report differences in GHG emissions between manure and mineral fertilizers (urea, urea-ammonium nitrate and ammonium nitrate) (Sistani *et al.*, 2011), emphasizing the complexity of soil GHG emissions and the multitude of factors that need to be considered when proposing mitigation practices (e.g. soil type and condition, climate conditions, manure composition and application method).

Capturing CH_4 produced once the manure has been applied to soil is not feasible and, therefore, most practices to prevent CH_4 emissions from land applied manure focus on preventing anaerobic conditions or reducing the degradable C flux to the soil at the placement site. Research reports on CH_4 and N_2O emissions following application frequently show a wide range of results. Authors commonly note that many variables in manure, application technique, soil type and management, soil moisture and climate can impact emissions.

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[43]. 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).

Components of the microbial biomass in the soil use CH_4 as a C source and therefore the soil is often a CH_4 sink. Only when CH_4 concentrations exceed the metabolic capacity of the soil, or when the aerobic metabolism of the soil biota is inhibited throughout the soil column, are CH_4 emissions significant after land application of manure. Therefore, promoting the aerobic metabolic path and reducing CH_4 load are other approaches used to reduce CH_4 emissions after manure injection (Rodhe *et al.*, 2006).

A note of caution is necessary because CH_4 emissions from manure injected into soil are relatively low when compared with the reduction in NH_3 volatilization obtained through subsurface injection. Powell *et al.* (2011c) investigated the NH_3 volatilization mitigating potential of three methods of stored dairy slurry application: surface broadcast, surface broadcast followed by partial incorporation using an aerator implement, and injection. Slurry total N loss was 27.1 percent (20.5 percent as NH_3 and 6.6 percent as nitrate), 23.3 percent (12.0 percent as NH_3 and 11.3 percent as nitrate), and 9.1 percent (4.4 percent as NH_3 and 4.7 percent as nitrate), respectively. The authors measured that although slurry incorporation decreased total N loss, the conserved N did not significantly impact crop yield, crop N uptake or soil properties at the end of the trial. The authors explained the lack of response to conserved N with the relatively small differences in slurry N remaining after N loss and the relatively large amount of soil N mineralization rate in the high fertility soil at the study site.

Unlike CH_4, most of the N_2O is produced after the manure has been applied to the soil. 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 are options to reduce N_2O emissions that can be achieved through the manure application method. In the first few weeks after application, manure injection often increases N_2O emission compared with surface applied manure.

---

[43] See Flessa and Besse (2000); Külling *et al.* (2003); Clemens *et al.* (2006); and Amon *et al.* (2006).

Dilution, solid separation and anaerobic digestion pre-treatments of manure before injection reduce the availability of degradable C and as a result, tend to decrease N_2O emission[44]. A number of authors[45] have noted that wet soils tend to promote N_2O emissions and that application timing can be important. On many soils, simply avoiding application before a rain event can avoid spikes in emission rates. Maintaining soil pH above 6.5 was shown by Mkhabela *et al.* (2006) to help reduce N_2O emissions. Nitrous oxide 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. Much work is needed to further investigate these manure application mitigation strategies.

Reduced CP in the animal diet produces manure with a slower N mineralization rate that releases less plant-available N (Powell and Broderick, 2011). Therefore, changes in manure application rate recommendations are needed to reflect N cycling from modified diets. At equal N application rate, however, whole-crop barley yield was not different between manures from dairy cows fed high- (16.8) or low-CP (14.8 percent) diets (Lee *et al*., 2013). To minimize N_2O production in all cases, manure application rates should be coordinated with the amount of mineral fertilizer applied, and consideration should be given to application timing and method to prevent application of N in excess of plant requirements.

> *Overall, lowering the concentration of N in manure, preventing anaerobic conditions or reducing concentration of degradable manure C are successful strategies for reducing GHG emissions from manure applied to soil. Separation of manure solids and anaerobic degradation pre-treatments can mitigate CH_4 emission from subsurface-applied manure, which may otherwise be higher than from surface-applied manure. Timing of the manure application (e.g. avoiding application before a rain) and maintaining soil pH above 6.5 may decrease N_2O emissions.*

Urease and nitrification inhibitors

Microbial processes that result in N_2O production can be manipulated through the use of chemical additives. Nitrification inhibitors [the most widely used are dicyandiamide (DCD) and nitrapyrine] were found to reduce the amount of N_2O produced under controlled experimental or field conditions[46].

Urease inhibitors are effective when applied to urine before it is mixed with soil or faeces and therefore has limited applicability to animal production systems or waste handling systems in which faeces and urine are separated after mixing. In open lot feedlots, however, urease inhibitors have been reported to effectively decrease NH_3 losses. For example, Varel *et al.* (1999) treated feedlot pens with urease inhibitors, cyclohexylphosphoric triamide and N-(n-butyl) thiophosphoric triamide. While no urea was found in the control pens, the treated pens retained significant amount of urea for up to 14 days following treatment. Treating the pens weekly for six weeks further increased urea conservation, respectively

---

[44] See Thompson *et al.* (1987); Flessa and Besse (2000); Külling *et al.* (2003); Amon *et al.* (2006); Clemens *et al.* (2006); and Velthof and Mosquera (2011).

[45] See Christensen (1983); Wagner-Riddle and Thurtell (1998); Rochette *et al.* (2004); Mkhabela *et al.* (2006); Hayakawa *et al.* (2009); Hernandez-Ramirez *et al.* (2009a, 2009b); Sauer *et al.* (2009); Smith and Owens (2010); Tenuta *et al.* (2010); and Meade *et al.* (2011).

[46] See Thompson *et al.* (1987); De Klein *et al.* (1996, 2001, 2011); Di and Cameron (2002, 2003, 2012); and Dittert *et al.* (2001).

reducing NH_3 volatilization losses. Contrasting with urease inhibitors, nitrification inhibitors were found to be effective in reducing N_2O emissions 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.*, 1996, 2001, 2011; Di and Cameron, 2002, 2003, and 2012). Luo *et al.* (2008) reported up to 45 percent reduction in N_2O emissions from dairy cow urine applied to various soils in New Zealand by the nitrification inhibitor DCD and pointed out that the effectiveness of these compounds may be reduced under heavy rainfall. Recent national trials in New Zealand reported an average N_2O reduction by DCD of 50 percent (Gillingham *et al*., 2012).

Application of DCD has also resulted in a dramatic 68 percent reduction in nitrate leaching losses from a deep sandy soil pasture of perennial ryegrass and white clover (Di and Cameron, 2002, 2005). In addition, Ca^{2+} and Mg^{2+} leaching were reduced by 51 percent and 31 percent, respectively, and herbage DM yield in the urine patch areas was increased by 33 percent (Di and Cameron, 2005). A review by de Klein and Monaghan (2011) suggested a potential reduction in nitrate leaching of up to 60 percent and N_2O emissions of up to 55 percent with DCD.

It has also been pointed out that the effectiveness of the nitrification inhibitors (specifically DCD) depends largely on temperature, moisture and soil type. For example, the longevity of DCD decreases with increasing soil temperature (Kelliher *et al.*, 2008; de Klein and Monaghan, 2011). Some studies have suggested potential increase in NH_3 volatilization and ammonium leaching due to increased ammonium accumulation in soil. It has been shown that DCD may not be effective in reducing nitrate leaching in soils that leach substantial amounts of ammonium, which is also influenced by rainfall (de Klein and Monaghan, 2011).

Results of the combined use of nitrification and urease inhibitors have been inconclusive (Khalil *et al.*, 2009; Zaman and Blennerhassett, 2010). Urease inhibitors inhibit urea hydrolysis to ammonium and thus directly affect substrate availability for NH_3 volatilization. A recent review of the literature, and using New Zealand as a case study, indicated that an urease inhibitor – N-(n-butyl) thiophosphoric triamide (nBTPT), in this case – was effective in inhibiting urea hydrolysis with an average NH_3 emissions reduction of 53 percent - from 11 to 93 percent (Saggar *et al.*, 2012). Because ammonium is also a source of nitrate leaching and N_2O emissions, it is expected that inhibition of urea hydrolysis will affect all three pathways of N losses in soil, but this has not been consistently observed (Khalil *et al.,* 2009; Zaman and Blennerhassett, 2010).

As stated earlier, nitrification inhibitors can increase soil ammonium and thus potentially increase NH_3 losses, while urease inhibitors prolong the stability of urea. If, however, nitrification inhibitor activity is meanwhile decreased, preservation of N as urea may not decrease consequent losses of N as nitrate or N_2O. This scenario is also questioned on the basis of different half-lives of urease and nitrification inhibitors (de Klein and Monaghan, 2011).

Advancements in plant biotechnology and microbial enzymology may offer new opportunities for reducing manure-amended soil N_2O emissions. Richardson *et al.* (2009) proposed that soil N_2O emissions from bacterial denitrification processes result from incomplete reduction of N_2O to N_2. These authors suggested several potential ways of enhancing this final step in the denitrification process, namely: (1) increasing soil copper (Cu) availability to provide sufficient Cu_A and Cu_Z, cofactors needed for biosynthesis or assembly of

N_2OR (N_2O reductase); (2) better understanding and regulating of N_2OR activities (enzyme repair and de novo synthesis); and (3) use of plants to "scrub" N_2O emissions by expressing bacterial N_2OR in plants.

> *Nitrification inhibitors offer promise for reducing N_2O emissions from intensive livestock production systems, but result in limited benefits to the producer apart from reducing N losses. Urease inhibitors are effective in preserving urea and reducing NH_3 volatilization. However, urease inhibitors may result in increased N_2O emissions due to potential increase in ammonium and subsequently nitrate concentration in soil.*

Control of manure greenhouse gas emissions through grazing practices

Nitrous oxide emissions can be particularly high in intensive pasture systems due to high N concentration in urine as a result of high CP content of the pasture (typically, 22 to 28 percent CP, DM basis, in New Zealand, for example), and there are many reports on the relationship between the placement and chemical composition of urine and soil nitrification and denitrification processes[47].

Eckard *et al.* (2010) pointed out that the effective N application rate within a urine patch from a dairy cow on pasture is between 800 and 1 300 kg N/ha, and N is deposited at concentrations that are orders of magnitude greater than the utilization capacity of the soil-plant system. These authors suggested that a more uniform distribution of urine throughout the paddock would reduce the effective N application rate, which should translate into a reduction in N_2O emissions.

These effects are often compounded by high fertilizer N application rates to stimulate grass growth, which further increases urinary N concentration. De Klein *et al.* (2001) showed a 40 to 57 percent reduction in N_2O emissions when grazing was restricted in the late humid New Zealand autumn to three hours per day. This reduction was attributed to diminished N input during conditions most conducive to N_2O emissions in New Zealand. 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 percent.

Nevertheless, keeping the animals off the paddocks, in "stand-off" or "feed pads" for most of the day during the wet months of the year (autumn-winter), has been shown to be an effective N_2O mitigation practice in intensive grazing systems (de Klein, 2001; de Klein *et al.,* 2002; Luo *et al.*, 2008b). Not allowing grazing during wet weather also increases pasture productivity due to reduced sward damage and soil compaction (de Klein, 2001). One must keep in mind, however, that this practice results in much greater NH_3 emissions (Luo *et al.*, 2010) due to urine and faeces being excreted and allowed to mix in the stand-off/feed area.

On the other hand, reduced grazing intensity has resulted in increased N_2O emissions in temperate zones with long freeze thaw cycling pastures (Wolf *et al.*, 2010). This increase in N_2O emission from reduced grazing was attributed to increased microbial activity during winter and early spring thaw resulting from increased leftover pasture biomass.

---

[47] See Ambus *et al.* (2007); Bhandral *et al.* (2008); Bol *et al.* (2004); Comfort (1990); Luo *et al.* (2008a); Rodhe *et al.* (2006); and Velthof and Mosquera (2011).

By restricting grazing when conditions are most favourable for N_2O formation, more even distribution of urine and optimizing fertilizer application are possible N_2O mitigation options for ruminants on intensively-managed pastures.

Cover cropping

Agronomic practices such as intensifying cropping frequency, increasing use of forages in crop rotations, reducing tillage intensity and frequency, better crop residue management and adopting agroforestry can all have a significant impact on soil C sequestration, although, according to some reports, the contribution of agricultural soil C sequestration to overall GHG emissions may be relatively small and the storage reversible (Hutchinson *et al.*, 2007).

Cover cropping can reduce soil erosion, improve soil quality and fertility, water, weed, disease, and pest management, and enhance plant and wildlife diversity on the farm (Lu *et al.*, 2000; Haramoto and Gallandt, 2004). In some production systems, cover cropping can also increase crop yields (Miguez and Bollero, 2007) and reduce input costs/increase farm profitability by reducing N fertilizer use, improving P availability and reducing weed control cost (Lu *et al.*, 2000; Stockwell and Bitan, 2012; Kassama *et al.*, 2012).

Reduction of N fertilizer use by growing leguminous cover crops has a direct mitigation effect on soil N_2O emissions by reducing soil nitrate availability and potential for leaching (Christopher and Lal, 2007). Through their symbiotic relationship with *Rhizobium* (root nodule bacteria), legumes fix atmospheric N, converting it to ammonium, which is consequently incorporated into plant AA and proteins. Thus, inclusion of legumes in plant rotation and consequent incorporation of legume residues into agricultural soils enhances plant-available inorganic N and organic soil N (Heichel, 1987).

A combination of cover cropping with other soil conservation practices can further improve soil quality and reduce GHG emissions. The effect of cover cropping on soil GHG fluxes, however, has not been consistent[48]. A review of soil organic C sequestration and GHG emissions from agricultural activities in the southeastern United States found that combining cover cropping with no-tillage enhanced soil organic C sequestration compared with no-tillage and no cover cropping (0.53 vs 0.28 Mg ha/yr; Franzluebbers, 2005). Similar results have been reported for cotton (Causarano *et al.,* 2006), but the C sequestration benefits were minimal and the effect on N_2O emissions were inconsistent in a corn/soybean rotation system (Bavin *et al.,* 2009).

Liebig *et al.* (2010) reported no net GHG mitigation benefit from incorporating a rye cover crop during the fallow phase of a dryland wheat cropping system under no-till management, and similar inconclusive results were reported by a Canadian study (VanderZaag *et al.*, 2011). In a different production system in California's Central Valley, a simulation analysis of soil conservation practices for several crops (beans, corn, cotton, safflower, sunflower, tomato and wheat) found that, compared with conventional agricultural management, cover cropping had the largest potential to mitigate soil GHG fluxes resulting in a net reduction of 752 to 2 201 kg CO_2-eq/ha/yr (with conservation tillage having the smallest

---

[48] See Franzluebbers (2005); Bavin *et al.* (2009); Kallenbach *et al.* (2010); de Gryze *et al.* (2010, 2011); and Borgen *et al.* (2012).

mitigation potential) (de Gryze *et al.,* 2010). Similar conclusions were drawn by the authors for alfalfa, melon and sunflower (de Gryze *et al.*, 2011).

> *Overall, cover cropping is beneficial for soil quality and agronomic characteristics and may increase crop yield and farm profitability. Cover crops can increase plant N uptake and decrease accumulation of nitrate, and thus reduce N_2O production through denitrification, but the results on overall GHG emissions have not been consistent. Interactions with other soil conservation practices are significant (tillage system, for example) and must be considered when the goal of cover cropping is reducing whole-farm GHG emissions.*

Other manure treatments

There are many waste treatment systems that are used in processing of human wastes. Few of these technologies are used practically for treatment of livestock wastes. Several studies have reported treatments other than those reported in sections above. Two biological treatments have been demonstrated to reduce emissions. In a laboratory study, Luth *et al.* (2011) demonstrated that earthworm inclusion in a vermifilter fed with swine manure provided a CH_4 sink and decreased emissions of NH_3 and N_2O emissions. Fukumoto *et al.* (2006, 2010) demonstrated that the addition of nitrite-oxidizing bacteria to swine manure reduced N_2O emissions up to 80 percent.

ANIMAL HUSBANDRY

This section deals with mitigation options that reduce Ei by increasing herd productivity and enhancing animal health and longevity while keeping GHG output constant (or increasing it proportionally less than productivity). Mitigation practices addressed here are intrinsically related to local governmental policies and application depends heavily on political will, incentives for farmers and availability of resources.

Enhancing animal productivity

Animal productivity has several dimensions including animal genetics, feeding, reproduction, health and overall management of the animal operation. As discussed earlier, in many parts of the world, the single most effective GHG mitigating strategy is to increase animal productivity, which may allow a reduction in animal numbers providing the same edible product output at a reduced environmental footprint. With time, increasing animal productivity can significantly reduce the number of animals needed for the national herd.

Such reduction in animal numbers was the single most influential mitigation strategy which reduced significantly the C-footprint of the United States dairy industry (Capper *et al.*, 2009). Similarly, in the Netherlands with a milk quota system, milk production per cow increased from 6 270 kg fat and FPCM/yr in Kyoto base year 1990 to 8 350 kg FPCM/yr in 2008, with a concomitant CH_4 decrease from 17.6 to 15.4 g/kg FPCM, respectively (Bannink *et al.*, 2011).

Similar progress has been made by the pork industry. As an example, hogs marketed in the United States increased by 29 percent between 1959 and 2009, while the size of the breeding herd decreased by 39 percent. Feed conversion efficiency increased by 33 percent, feed use decreased by 34 percent and the C footprint per 454 kg of hot dressed carcass weight produced decreased by 35 percent. The litter size increased from 7.10 in 1974 to

9.97 piglets in 2011 and the amount of pork produced from a breeding animal increased for the same period from 775 kg to 1 828 kg (National Pork Board, 2012).

In developing countries, smallholders typically rely on a greater number of low-producing animals instead of a smaller number of higher-producing animals (Tarawali *et al.*, 2011). As pointed out by these authors, there are two constraints for increasing animal production: the genetic potential of the animals and the availability of quality feed. Undoubtedly, there is a significant potential for increased production (to achieve the genetic potential of the animals) by better feed management and proper feeding in developing countries.

This potential, although smaller, also exists for intensive production systems in developed countries. Using a partial LCA, Bell *et al.* (2011) demonstrated that improvements in milk production (in their example, from about 23 to 28 kg ECM/day) and feed efficiency can significantly reduce GHG emissions and land use of the dairy herd. Nevertheless, the potential for improvement in animal production may be smaller in developed countries where animals are already relatively high-producing and efficient.

Selection for high milk production in dairy cows, for example, should not be at the expense of decreased productive life, increased death rate and a decline in fertility[49]. Impaired reproductive performance also has a significant impact on farm profitability and cannot be fully compensated by increased milk production, as demonstrated by Evans *et al.* (2006) for commercial dairy herds in Ireland.

Apart from productivity, however, there are management practices in intensive production systems that can improve overall animal performance and lifetime productivity (such as improved animal health, heifer management and fertility; Place and Mitloehner, 2010). By some estimates, extended lactation[50] can reduce enteric CH_4 emission from dairy production systems by 10 percent (Smith *et al.*, 2007a). However, this may not be a feasible alternative to a 12-month lactation cycle in some production systems (Butler *et al.*, 2010). In intensive dairy systems, similar effects may be produced by reducing the dry period, with or without recombinant bovine somatropin (rbST) use[51]. In some systems, however, reducing or eliminating the dry period decreased early lactation and 305-day milk yields, increased overall culling rate (Pinedo *et al.*, 2011), and may not be suitable for all cows and all herds (Marett *et al.,* 2011; Santschi *et al.*, 2011).

Much progress in reducing GHG Ei from ruminants in the developing world can be achieved by increasing animal productivity (milk or meat). As the analysis of the dairy sector by Gerber *et al.* (2011) demonstrated, there is a great difference in GHG emissions depending on milk production of the cows, with as much as a tenfold variation between countries or regions with high and low milk production. Flachowsky (2011), for example, estimated that a dairy cow producing 40 kg milk/day would have about 50 percent lower CO_2-eq emissions per kg of edible protein than a cow milking 10 kg/day. Similarly, emissions would be about 70 percent lower from beef cattle gaining 1.5 vs 1.0 kg/day, 40 percent lower from a growing or fattening pig gaining 900 vs 500 g/day, and 60 percent lower from a laying hen with 90 vs 50 percent laying performance.

---

[49] See Hare *et al.* (2006); Miller *et al.* (2008); and Norman *et al.* (2009).

[50] See van Amburgh *et al.* (1997); Auldist *et al.* (2007); Kolver *et al.* (2008); and Grainger *et al.* (2009b).

[51] See Annen *et al.* (2004); Rastani *et al.* (2005); and Klusmeyer *et al.* (2009).

To illustrate the effect of productivity on GHG emissions, data for the dairy sector by FAO (Gerber *et al.*, 2011) were used. According to these data, the annual milk production per cow for North America was approximately 8 900 kg in 2010 and in South and Southeast Asia (SEA) was 2 800 kg/yr for specialized dairy systems (1 000 kg/yr for unspecialized systems). Using the Gerber *et al.* (2011) relationship for CO_2-eq (CO_2-eq, kg/cow/yr = 0.8649 × milk yield, kg/cow/yr + 3315.5; and assuming milk yield is as FPCM), it can be calculated that a North American cow will produce about 11 000 kg of CO_2-eq/yr and a SEA cow about 5 700 kg CO_2-eq/yr, which is 1.24 and 2.05 kg CO_2-eq/kg milk, respectively. If milk production in SEA is increased by 30 percent (average milk production of about 3 600 kg/cow/yr) without a change in GHG emissions, the CO_2-eq output will decrease to 1.78 kg/kg milk.

Blümmel *et al.* (2009) estimated that increasing milk yield per animal in India from the national average of 3.61 litres/day to 6 to 9 litres/day was possible using currently available feed resources, which would potentially reduce CH_4 production in that country from 2.29 Tg to 1.38 Tg/yr.

Another example of how increased productivity, through increased feed quality, can decrease enteric CH_4 per unit of product was provided by Waghorn and Hegarty (2011). These authors calculated that growing lambs on higher quality pasture (20 percent higher ME value) had higher gain and about 50 percent lower enteric CH_4 emission per unit of gain (i.e. Ei). These gains may come from improved animal genetics (see discussion in following sections) and through improved animal nutrition.

In most situations, improved nutrition would mean increased forage quality, i.e. digestibility, or increased grain inclusion in the diets of ruminants. The latter is a controversial proposition. Although ruminant production systems based on concentrate feeds can be more efficient from the animal perspective and emit less GHG per unit of product (Beauchemin *et al.*, 2010), LCA are needed to determine if this is the case when emissions associated with grain and forage production, transportation and processing are considered.

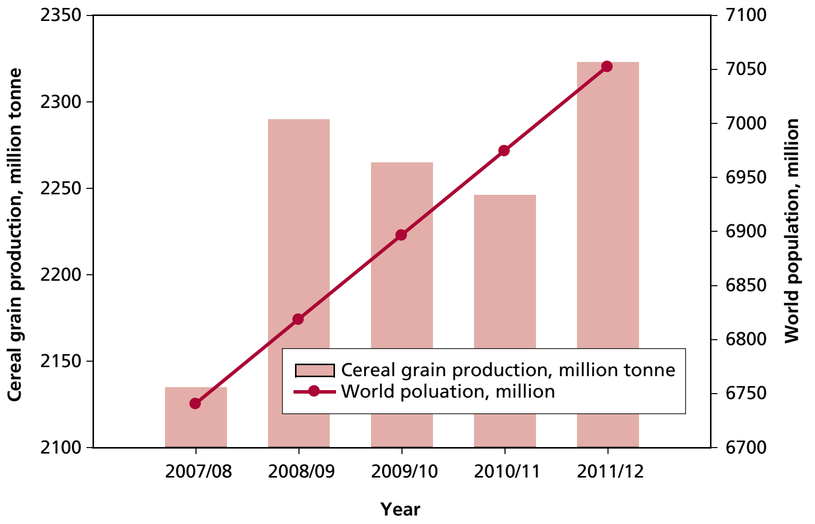
This may not necessarily be the case if all inputs are included in calculating Ei for intensive grain-finished vs extensive, grass-finished beef (Waghorn and Hegarty, 2011), particularly when C sequestration by grasslands is adequately considered. In addition, increasing animal production in the developing world may be a costly and long-term process because it will require both genetic improvements and improvements in animal nutrition.

High-quality pastures may not be a viable option for improving animal nutrition in many regions, in which case, improvement in production has to come through feeding concentrate feeds.. As the rate in cereal grain production has generally followed the rate of world population growth (Figure 10; data from FAO; http://www.fao.org/worldfoodsituation/wfs-home/csdb/en and http://www.geohive.com/earth) and human nutrition is expected to improve in the developing world, it is questionable if more grain will be available for feeding ruminant animals. Growing ruminant is much less efficient in utilizing grain for BW gain than poultry or swine, but dairy cows could be as efficient (depending on the level of production) as monogastric animals in producing edible protein[52]. Nevertheless, it is questionable in the long-term whether increasing the inclusion of grain in the ration of cattle, buffalo or sheep and goats can be an economically feasible strategy to increase milk and particularly meat production and thus reduce the environmental footprint of livestock.

---

[52] See Flachowsky (2002, 2011); Gill *et al.* (2010); and de Vries and de Boer (2010).

FIGURE 10
World cereal grain production and population growth



Within dairy production systems, grassland-based systems have been estimated to have generally higher (by about 50 percent) GHG emissions per unit of FPCM than mixed farming systems, although some grazing systems in temperate regions show low Ei (FAO, 2010). Organic dairy production systems also have higher GHG Ei than conventional dairy systems, as shown in some analyses in the United States and Europe (Heller and Keoleian, 2011; Kristensen *et al.*, 2011), although this is probably not always the case and depends on fertilizer inputs for crop production and level of animal productivity (Martin *et al.*, 2010a).

The environmental efficiency of pasture-based dairy production systems can be improved by a variety of best-management practices, as demonstrated in a modelling exercise by Beukes *et al.* (2010). These authors estimated that implementation of a combination of practices including improved reproductive performance leading to low involuntary culling, using crossbred cows with high genetic merit for milk solids, and improved pasture management to increase average pasture and silage quality could decrease GHG emissions by 27 to 32 percent on a pasture-based New Zealand dairy farm. Similar results were reported earlier by Basset-Mens *et al.* (2009).

Achieving the genetic production potential of the animal is dependent on proper nutrition. Underfeeding due to insufficient feed availability or improper diet formulation can be a common problem in developing but also in developed countries. A field study with commercial dairy herds in the United States concluded that efforts to minimize feed waste (i.e. feed cost savings) must ensure that cows receive adequate nutrients to avoid suppression of genetic potential for milk yield (Dekleva *et al.*, 2012).

A study from Ireland investigated the response of Holstein-Friesian cows, of medium or high genetic merit, fed an adequate supply of grass to half and twice the industry norm level of concentrate supplementation (Kennedy *et al.*, 2001). The study found that the low concentrate feeding system restricted the ability of the high genetic merit cows to express fully their genetic potential for milk production. The difference in milk yield between genotypes was much larger in the high-concentrate feeding system than in the low-concentrate systems. However, an important conclusion of this study was that high-concentrate supplementation systems, although yielding more milk and better utilizing the genetic potential of the animal, may not be economically feasible when milk price is low and feed cost is high.

A New Zealand study with cows on pasture concluded that cows with high genetic potential for milk yield undergo higher relative energy deficits under grazing dairy systems, resulting in lower substitution rates, higher milk responses to supplements, but also lower body condition score, which in turn leads to lower reproductive performance (Baudracco *et al.*, 2010). The authors also pointed out that inclusion of concentrate supplements on pasture with a concomitant increase in stocking rate can have synergistic effects on improving productivity of grazing dairy systems. Apparently, increasing stocking rate alone would result in decreased production per animal and is expected to increase GHG emissions per unit of milk. The level of supplementation required per cow and the optimum stocking rate depend on the genetic potential of the cow, the size of the responses to supplement, forage availability, and the value of milk and costs of feeding supplements.

Achieving the genetic potential of the animal is critically important, but it is also as important not to import genetics into climates and management environments where high-producing animals can never achieve their potential and will in fact perform worse than native breeds or crossbreeds due to management, disease or climatic challenges. The Holstein dairy cow, for example, has a high genetic potential for milk production, which translates into low GHG emissions per unit of product, but its importation into environments that it cannot adapt to leads to poor health, milk production and reproduction (compounded with the already low genetic merit of the breed for this trait) resulting in underperformance and long-term inefficiency of the production system (Harris and Kolver, 2001; Evans *et al.*, 2006; Madalena, 2008). As pointed out by Harris and Kolver (2001), the failure of the Holstein breed to maintain high reproductive efficiency appeared to be one of the main reasons for the reduced survival of the breed within the pasture conditions of New Zealand and resulted in a substantial economic advantage for farmers rearing the local cross-bred dairy cows.

Increasing animal productivity can be a very successful strategy for mitigating GHG emissions from the ruminant sector in both developed and developing countries, with a greater mitigating potential in developing countries. Improving forage quality, grain inclusion in the diet, achieving the genetic potential of the animal for production through proper nutrition and use of local breeds or crossbreeds are recommended approaches for improving animal productivity and reducing GHG emissions per unit of product. The trend is less clear for monogastric species as two trends tend to counterbalance each other: on one hand, productivity can reduce feed consumption (and thus emissions from production of feed) and manure emissions per unit of product ; but on the other hand, highly productive animal require higher quality (and emission intensity) feeds.

Recombinant bovine somatotropin (rbST)

An additional animal management practice that can indirectly reduce emissions by improving productivity in dairy cattle is the use of rbST. Capper *et al.* (2008) employed a mathematical modelling approach to estimate the impact of rbST use on individual cow- and industry-wide scales, assuming an increase in milk production of 4.5 kg/day (an optimistic assumption according to European data; Chilliard *et al.*, 1989). The results of the analysis suggested that rbST use may reduce CH_4 output by 7.3 percent per unit of milk produced.

Use of rbST has been controversial, and its use for milk production is banned in Canada, Japan, the European Union, Australia and New Zealand. Limited evidence suggests that the use of rbST may increase the risk of clinical mastitis and of cows failing to conceive, and also may increase the risk of developing clinical signs of lameness (Dohoo *et al.*, 2003). Should the use of rbST really have a negative influence on fertility and animal health, then the reduction in enteric CH_4 emission estimated by Capper *et al.* (2008) would be smaller or even absent. In addition, this mitigation practice is likely to be applicable only in intensively-managed animal production systems.

> *Enhanced productivity and feed efficiency with rbST would reduce Ei but applicability of this mitigation practice is limited to regions where rbST use is allowed. There are also questions of economic feasibility and effects of rbST on animal health and fertility.*

Animal genetics

Improvements in animal genetics, coupled with improvements in diet management, can lead to a significant reduction in GHG emissions per unit of product from livestock production systems, as shown with the Australian beef industry (Henry and Eckard, 2009). Some studies using beef cattle indicate that animals with low RFI can produce up to 28 percent less enteric CH_4 (Nkrumah *et al.* 2004; Hegarty *et al.* 2007).

According to Herd and Arthur (2009), variation in RFI can be attributed to variation in protein turnover, tissue metabolism and stress (37 percent), with lesser contributions from digestibility (10 percent), heat increment and fermentation (9 percent), physical activity (9 percent), and body composition (5 percent).

An extended review of the topic was recently published by Waghorn and Hegarty (2011). These authors concluded that there was little evidence that efficient animals have a different CH_4 yield per unit of DMI. Further, they pointed out the need to select high-producing animals because this reduces emissions per unit of product. The extent to which CH_4 can be reduced by selection for RFI depends on the heritability of the trait, dispersal of efficient animals through all populations and their resilience in a production system.

Selection for individuals that have a lower than average CH_4 yield requires: (1) that the host animal controls its microflora, and that the trait is heritable; (2) that selection for low CH_4 producers is more important to animal producers than other traits (e.g. productivity, fertility); and (3) that the effect is persistent and applicable to all levels of production. Thus, the immediate gain in GHG reductions through RFI is quite uncertain. De Haas *et al.* (2011) estimated a heritability of RFI in dairy cattle of 0.40. Genetic variation suggests that a reduction in predicted CH_4 production in the order of 11 to 26 percent is theoretically possible.

Interestingly, genomic selection tools can further increase the reduction in CH_4 production, but effective application requires significant international effort and collaboration to bring together relevant data. Modern molecular techniques have revealed much greater diversity in the ruminal microbial system than previously known. Significant collaborative efforts are underway to understand the interactions between host animal and its microbiome and potentials for selecting more efficient animals or animals producing less enteric CH_4 (McSweeney and Mackie, 2012). These authors indicated that, based on the analysis of global datasets, the majority (> 90 percent) of rumen methanogens are affiliated with genera *Methanobrevibacter* (> 60 percent), *Methanomicrobium* (~15 percent), and a group of uncultured rumen archaea commonly referred to as rumen cluster C (~16 percent; recent data have indicated that these methanogens produce greater amounts of CH_4 relative to *Methanobrevibacter*). Animal species, breed, and environmental conditions all have been shown to affect ruminal microbial diversity, which could potentially be used to select animals with lower CH_4 emitting potential or manipulate the ruminal ecosystem to raise animals producing less enteric CH_4 per unit of digested feed (see also Abecia *et al*., 2011). Permanent inoculation of the rumen with foreign microbes is rare, but has been successful under certain conditions (Jones and Lowry, 1984; Jones and Megarrity, 1986) and may be a possible mitigation approach in the future.

Type of diet fed and forage or pasture quality have an important role in selecting low-CH_4 emitters through selection for RFI. Jones *et al.* (2011), for example, concluded that the hypothesis that low-RFI cows produce less CH_4 was not supported on low-quality summer pasture but was supported when cows were grazing high quality winter pastures. McDonnell *et al.* (2009) concluded that differences in digestive capacity for some dietary fractions – but not ruminal CH_4 production – may contribute to differences in RFI between cattle. In the McDonnell *et al.* (2009) study with Limousin × Friesian heifers, DMI and CH_4 emission did not differ between low- and high-RFI animals, but CH_4 expressed per unit feed DMI was significantly higher for the low-RFI (i.e. efficient) animals.

The government of Alberta in Canada has developed four science-based protocols that outline steps to mitigate GHG emissions from the specific beef cattle production system of western Canada (Basarab *et al.*, 2009). One of the quantification protocols is focused on selection for low RFI. Two other protocols, related to animal genetics, nutrition and management, are aimed at reducing age at harvest in young cattle and reducing the number of days that cattle are on feed in the feedlot. According to these protocols, these practice changes have the potential to reduce GHG emissions from cattle by 0.02 to 1.0 tonne of CO_2-eq per animal (Basarab *et al.*, 2009) and are promising mitigation practices that may be applicable to various production systems.

As indicated earlier, RFI-selection is a promising technology but with uncertain returns. In addition, the current system for estimating RFI requires significant investments (animal identification and accurate measurements of feed intake and animal production; Waghorn and Hegarty, 2011) that are unlikely to take place in developing countries in the short-term. The concept of genetically modified animals, designed to have a lower environmental footprint (primarily, by having higher feed efficiency), although not universally accepted, may also offer an opportunity for more efficient animal production in the future (Niemann *et al.*, 2011).

Breeds may differ in their efficiency of feed utilization, which may be explored as a long-term GHG mitigation option. Breeds have different maintenance requirements and efficiency of energy use for maintenance. A long-term study investigated maintenance energy requirements and efficiency of ME use for gain between beef and dairy cattle breeds (Solis *et al.*, 1988). The ME requirement for maintenance was 91.6, 93.8, 95.3, 115.7 and

140.4 kcal/kg$^{0.75}$ for Angus, Brahman, Hereford, Holstein and Jersey, respectively. The efficiency of ME use for tissue energy gain or loss was 80.6, 66.8, 66.0, 36.5 and 36.2 percent, respectively. These authors concluded that maintenance energy requirements for weight and energy equilibrium were lower and the efficiency of ME use was higher in beef breeds and their crosses than in dairy breeds and their crosses, which was explained by differences in body composition and physiological priorities.

In the case of dairy cows, selection for gross feed efficiency (i.e. milk per unit of feed) may not be advantageous because of high genetic correlation between gross feed efficiency and milk yield (Korver, 1988; Ostergaard *et al.*, 1990). It is recognized now that intensive selection for one genetic trait leads to losses in other traits. Breeding for milk yield, for example, comes at the expense of beef traits, such as ADG and carcass quality, and secondary traits, such as reproduction, animal health, etc. (Østergaard *et al.*, 1990), which may not always be beneficial for the producer.

Østergaard *et al.* (1990) simulated an economic analysis of a highly-specialized dairy breed vs a combination use breed for the conditions of Denmark. The analysis showed a significantly higher farm net income with the combination breed: 33 European Currency Unit (ECU; no longer in use) per 1 000 kg 4-percent FCM vs 17 ECU for the specialized dairy breed in (milk yield of 9 500 kg vs 6 500 kg/lactation for the dairy and combination breed, respectively). However, the authors also estimated that genetic improvements in various traits for the specialized dairy breed (such as feed intake capacity and feed efficiency, beef quality traits, reproduction and health) can significantly increase the profit to a level comparable to or higher than the net income for the combination breed; the point being that genetic selection for one trait must be done cautiously with a consideration for gains and losses in related traits.

A Dutch study with Jersey cows vs a group of Holstein, Dutch Friesian, and Dutch Red and White cows found that the biological efficiency for milk production (energy in milk divided by net energy in feed) was 57 and 69 percent (all forage and 50:50 forage:concentrate diets, respectively) for the Jersey group vs 56 and 61 percent for the Holstein-Friesian group of cows (Oldenbroek, 1988). Similar higher efficiency for the Jersey breed was reported earlier by the same author with first lactation cows (Oldenbroek, 1986).

Grainger and Goddard (2004) carried out a comprehensive review of experimental data for feed efficiency of various dairy breeds (Holstein, Friesian, Jersey, and Holstein-Friesian × Jersey crossbred cattle) and locations (New Zealand, United States and Europe). Based on the available data, the authors concluded that Jerseys appear to have a higher feed conversion efficiency measured as milk solids per unit of DMI (from about -7 to about +19 percent more efficient than Holstein-Friesian cows). The authors also indicated that crossbred cows may have an advantage over the purebreds due to improvements in feed efficiency, health and fertility – partly due to heterosis, underlining the opportunity to use more Jersey semen for crossbreeding with the Holstein-Friesian breed.

However, a more recent comparison between Holstein, Danish Red, and Jersey cows did not find a clear advantage of the Jersey vs Holstein breed (Halachmi *et al.*, 2011). These authors reported lower peak milk yield, comparable lactation fat yield and lower protein yield for Jersey vs Holstein and Danish Red cows. Feed efficiency (kg DMI needed to produce 1 kg of milk) was lower for the Jersey breed (0.95 kg) than the Holstein (0.77 kg) and the

Danish Red (0.84 kg) cows. Efficiency for production of milk fat, however, was greater for the Jersey cows (15.4 vs 18.8 and 19.6 kg, respectively). In this study, Jersey cows were about 172 kg lighter than the other two breeds. Body weight is an important factor contributing to GHG emissions through energy requirement for maintenance. Smaller breeds may have a smaller C-footprint due solely to smaller BW. Capper and Cady (2012) estimated that the C-footprint per 500 000 tonnes of cheese produced would be 1 662 × 10^3 t of CO_2-eq lower for Jersey vs Holstein cows, partly due to a greater cheese yield but mostly due to a smaller BW of the Jersey cows.

The debate of milk component yields vs milk volume in relation to GHG emissions from the dairy industry is an interesting one. According to USDA-DHI 2011 records[53], the average milk yield and milk fat and protein content for Ayrshire, Brown Swiss, Jersey and Holstein[54] herds in the United States was: 7 020 kg/lactation with 3.95 and 3.17 percent fat and protein; 8 355 kg with 4.10 and 3.39 percent; 7 633 kg with 4.75 and 3.63 percent; and 10 617 kg with 3.66 and 3.07, respectively. Based on these data, fat and protein yields per lactation can be calculated at: 277 and 223 kg; 343 and 283 kg; 363 and 277 kg; and 389 and 326 kg, respectively. Thus, the Holstein breed has a clear advantage in terms of milk volume and milk fat and protein yields in the United States.

The importance of milk components is well-recognized by the dairy industry even to the extent that total milk solids are considered[55]. Fluid milk consumption in the United States represented 33 percent of all dairy products consumption in 2010[56]. The proportion of milk consumed as fluid milk is much greater in regions with high population density such as the Northeast and Mideast, which combined made up 35 percent of the total fluid milk consumption in the United States in 2011[57]. In these regions, there is not much demand for milk with fat (or even less protein) concentration greater than standard fat content of milk sold in the grocery outlets.

Thus, dairy breeds with higher milk yield but lower concentration of milk components, such as the Holstein breed (outperforming by a large margin the other dairy breeds in the United States) would have a clear advantage in terms of intensity of GHG emission and C-footprint per unit of milk[58] in areas where dairy products are consumed mostly as fluid milk. Increased protein and fat content of milk would be an important breed quality in areas where most of the milk is processed into cheese, such as the Pacific Northwest with only 5 percent of the fluid milk consumed in the United States in 2011[59].

Even in developing countries where feed resources may be limited, introducing genes for high production may be beneficial for the farmer. A large survey of smallholder dairy farms (average milk production was 1 425 litre/lactation) in the "drier transitional zones" of Kenya

---

[53] See http://aipl.arsusda.gov/publish/dayhi/current/hax.html; accessed on 12 July 2012.

[54] Only some breeds are used as examples.

[55] Including lactose, which is closely related to milk volume and does not contribute to cheese and butter yields.

[56] See USDA-ERS, http://www.ers.usda.gov/dayata-products/dayairy-data.aspx; accessed on 12 July 2012.

[57] See http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5090395&acct=dmktord; accessed on 13 July 2012.

[58] Cheese manufacturing has a greater environmental impact, primarily through energy consumption, than fluid milk; Milani *et al.*, 2011.

[60] Idaho, for example, with a population of just over 1.5 million, is currently the third largest milk producing state in the United States with more than 90 percent of the milk going into cheese production.

S. TORGUNRUDE AND AGRICULTURE AND AGRI-FOOD CANADA, T.A. MCALLISTER

photo 10
Cow-calf beef operation system in western Canada

showed that exotic dairy breeds (Friesian, Ayrshire, Guernsey and Jersey) adapted to the conditions of the survey regions were economically more efficient than the indigenous breeds (Sahiwal, Boran, Zebu and Zebu cross); Ayrshire achieved the lowest cost inefficiency (24.4 percent), followed by Friesians (25.1 percent) and Jersey (25.6 percent), with Sahiwal (28.43 percent) being the lowest cost inefficiency breed among the indigenous cattle (Kavoi *et al.*, 2010).

There is also an opportunity for introduction of more efficient breeds in developed countries. A three-year study in Switzerland investigated the performance of New Zealand Holstein Friesian cows under Swiss grazing conditions (60 to 65 percent of the diet was grazed pasture) in comparison with indigenous Swiss breeds. The results showed that the New Zealand cows were more efficient than the Swiss cows; with ECM per metabolic BW being 49.7 to 55.6 vs 44.2 to 46.6 kg/kg, respectively (Thomet *et al.*, 2010).

Another possibility for faster genetic improvement in some production systems is gender-selected (i.e., sexed) semen technology (see also *Animal fertility*). It has been suggested that application of this technology in the dairy industry will allow producers a more flexible selection to produce dairy replacement heifers from only the genetically superior animals in their herds (De Vries *et al.*, 2008). Having more genetically superior animals in the herd is expected to increase milk production per animal and thus reduce GHG Ei but may increase replacement rates and temporarily increase total milk supply (De Vries *et al.*, 2008). The gender-selected semen technology for producing heifers is of particularly high importance in reducing the number of dairy animals in countries like India where cattle are not slaughtered due to religious reasons (Harinder P.S. Makkar; personal communication, 2012). Higher cost and lower conception rate with gender-selected semen are some of the limitations of this technology that would have to be overcome (Weigel, 2004).

Animal genetics can also have a significant effect of GHG emissions from swine and poultry. As relatively very little enteric CH_4 is emitted from these animals, the majority GHG from swine and poultry operations (excluding feed production) are attributed to buildings, manure storage, and land application of manure. Thus, improving animal feed conversion efficiency, i.e. reducing the volume of manure produced while maintaining animal productivity, becomes a major strategy for mitigating CH_4 and N_2O emissions from these monogastric farm species. Animals with genetic lines predisposed to high feed efficiency excrete fewer nutrients in urine and faeces. Healthy herds also use feed efficiently and can reduce N excretion by 10 percent compared to unhealthy herds. Split-sex feeding enables producers to feed each sex closer to its nutritional requirements; for example, female turkey will require much less nutrients due to their smaller size than male turkey (Pennsylvania State University Extension; http://extension.psu.edu/aec/factsheets/greenhouse-swine-and-poultry, accessed on 9 February 9, 2013).

A study with 380 Duroc boars from seven generations and 1 026 Landrace pigs from six generations showed that measures of feed efficiency (feed conversion ratio and RFI) were moderately heritable (Hoque and Suzuki, 2008). Genetic and phenotypic correlations between ADG and measures of RFI were close to zero, which, according to the authors, indicated that selection for reduced RFI could be made without adversely affecting animal growth. A study with the French Large White reported large improvements in growth, feed efficiency, and carcass lean content of this breed between 1977 and 1998 (Tribout *et al.*, 2010). Another study from France investigated four pig breeds between 2000 and 2009 for estimates of genetic parameters for RFI, production traits, and excretion of N and P during growth (Saintilan *et al.*, 2012). Residual feed intake showed moderate heritability for all breeds (h^2 from 0.22 ± 0.03 to 0.33 ± 0.05) and was positively correlated with feed conversion efficiency. There was a significant breed effect on N excretion. The authors concluded that a selection index including RFI can be used for improvements in feed conversion efficiency, which would also lead to lower nutrient losses and consequently, decreased GHG emissions from manure.

> *The potential of using RFI as a selection tool for low CH_4-emitters is an interesting mitigation option, but currently there is little evidence that low-RFI animals have lower CH_4 emissions per unit of feed intake or product. Therefore, the immediate gain in GHG reductions through RFI is considered uncertain. However, selection for feed efficiency will yield animals with lower GHG Ei. Breed differences and maximum utilization of the genetic potential of the animal for feed conversion efficiency can be powerful GHG mitigation tools in both ruminants and non-ruminants. Reducing age at harvest and the number of days cattle are on feed in the feedlot can have a significant impact on GHG emissions in beef and other meat animal production systems.*

Animal health and mortality

Improving animal health and reducing animal morbidity and mortality in order to improve the efficiency of the animal production system are two opportunities to reduce both CH_4 and N_2O from enteric fermentation and animal manure. However, although the connections among animal health, mortality and productivity are obvious, few studies have examined their implications on CH_4 and N_2O emissions[60].

Improving the health of the animal and reducing mortality not only reduce the production of manure and therefore emissions of CH_4 and N_2O, but also benefit the livestock producer. The CH_4 and N_2O emission produced during the period the animal is grown to the productive stage are a net loss if the animal dies before its productive value is harvested, or its value is greatly reduced when productive potential is reduced due to poor health.

---

[60] See Hospido and Sonesson (2005); Bell *et al.* (2008) ; Dourmad *et al.* (2008) ; and Stott *et al.* (2010).

The opportunities to reduce CH_4 and N_2O from animal manure through improving animal health and reducing the productive mortality are especially important in places where the livestock production system is rudimentary or the application and dissemination of technology is difficult.

As livestock industries change and consolidate over time towards fewer farms with larger herds, the practice of veterinary medicine also changes its focus. The major focus of veterinary medicine for livestock production systems that rely on small herds is the eradication of clinical infectious diseases, with the emphasis on individual animal treatment. However, as herd size and animal productivity increase, the focus shifts towards preventive veterinary medicine and greater emphasis is placed on subclinical disease and systematic health management programmes that target increased productivity (LeBlanc *et al.,* 2006). Regardless of the developmental stage of a livestock production system, reduced mortality and morbidity lead to greater saleable output, diluting non-CO_2 emissions per unit product.

Taking the dairy industry as an example, lameness or injury (20.0 percent), mastitis (16.5 percent), and calving problems (15.2 percent) represent the three major reported causes of mature cow death in the United States (USDA, 2007). Both lameness (Warnick *et al.* 2001) and mastitis (Wilson *et al.*, 1997) also reduce milk output, increasing non-CO_2 GHG emissions per unit product.

Similarly, reproductive problems (26.3 percent), mastitis (23.0 percent), poor production (16.1 percent), and lameness or injury (16.0 percent) are the four major reasons for permanently culling cows from the United States dairy herd (USDA, 2007). According to LeBlanc *et al.* (2006), 75 percent of disease occurs within the first month after calving. In addition, 26.2 percent of dairy culls were reported to occur from 21 days before to 60 days after calving in a study on all Pennsylvania cows with at least one dairy herd improvement test in 2005 (Dechow and Goodling, 2008). Metabolic disorders related to calving also lead to culling and reduced milk production (Berry *et al.*, 2007, Duffield *et al.*, 2009).

Mathematical modelling approaches, including LCA and Markov chain simulation methods, were used to examine the effects of reduced incidence of mastitis on non-CO_2 emissions (Hospido and Sonesson, 2005). These authors predicted a reduction of 2.5 percent (GWP) to 5.8 percent (depletion of abiotic resources) if the clinical mastitis rate decreased from 25 to 18 percent and the subclinical mastitis rate decreased from 33 to 15 percent in Spain. Simulation results seem promising, but reliable quantitative estimates of the mitigation potential of improved health will require more research.

> *Improved animal health and reduced mortality and morbidity are expected to result in increased herd productivity, diluting non-CO_2 GHG emissions per unit product.*

Animal fertility[61]

Poor fertility increases GHG emissions from animal production systems[62]; this is primarily because poor fertility causes livestock producers to maintain more animals per unit of production and keep more replacement animals to maintain herd/flock size[63].

---

[61] Data from analysis of the literature on animal fertility are summarized in Table A4 (see Appendix 2).

[62] See Dyer *et al.* (2010); O'Brian *et al.* (2010); and Crosson *et al.* (2011).

[63] See Garnsworthy (2004); Berglund (2008); Wall *et al.* (2010); and Bell *et al.* (2011).

Garnsworthy (2004) provides an example of the relationship between improvements in dairy cow fertility in the United Kingdom and its impact on CH_4 and NH_3 emissions, concluding that improvements in fertility could reduce CH_4 emissions by 24 percent and NH_3 emissions by 17 percent, primarily by reducing the number of replacements in the herd.

In the global dairy industry, there has been a general decline in fertility that is indirectly associated with aggressive selection for production traits. Roughly one-third of the reduction in fertility in dairy cattle over the last 40 years is estimated to be associated with genetic selection for production and increases in inbreeding (Shook *et al.*, 2006; Huang *et al.*, 2010). However, this trend has recently been slowed and even reversed in developed countries due to the greater emphasis on fitness and fertility traits in selection indexes and management strategies in an effort to counteract these declines (Funk, 2006).

Nutritional status, timing of the initial insemination after parturition, and method and timing of pregnancy diagnosis of females are key factors that interact to determine fertility (Mourits *et al.*, 2000). In many parts of the world, especially developing countries, inadequate nutrition is the primary factor limiting fertility. However, even in these areas, there are low input approaches that can be, and in some cases are being, implemented to increase fertility. Examples of low input approaches to increase fertility include reducing inbreeding (Zi, 2003; Berman *et al.*, 2011), sire mate selection from highly fertile animals, reducing stressors and improving education about factors influencing fertility (Banda *et al.*, 2011).

Use of reproductive technologies where they are available and cost effective, such as genetic/genomic selection for fertility[64], artificial insemination (AI)[65], gender-selected semen (i.e. gender-selected semen)[66], embryo transfer[67] and estrous/ovulation synchronization[68], increases reproductive efficiency and reduces the number of animals and GHG Ei (Garnsworthy, 2004; Bell *et al.*, 2011).

In particular, failure to utilize AI where it is available and cost effective results in increased numbers of animals per farm (males) and reduced genetic merit for production and reproduction traits.

In this regard, there is growing evidence that governments of developing countries can effectively lead efforts to facilitate the use of AI and greatly accelerate genetic progress, provided these efforts include all stakeholders, are comprehensive and include improvements to facilities and markets (FAO, 2011a).

Choice of breed and mating strategies

Indigenous breeds reflect many generations of selection for ability to survive in environment-specific conditions and with local feed resources and management. Often equally important to smallholder farmers are appearance traits that may or may not be related to productivity; examples include coat colour, tail type and presence and type of horns (Gizaw *et al.*, 2011; Duguma *et al.*, 2010).

---

[64] See Tiezzi *et al.* (2011) and Amann and DeJarnette (2012).

[65] See Lopez-Gatius (2012).

[66] See Rath and Johnson (2008) and DeJarnette *et al.* (2011).

[67] See Hansen and Block (2004) and Longergan (2007).

[68] See Gumen *et al.* (2011).

Selection for survival (e.g. heat tolerance, parasite resistance) and appearance traits has, in many cases, come at the expense of fertility and production traits (Berman, 2011). In addition, there are numerous examples of introductions of non-adapted breeds into regions with the goal of realizing rapid gains in production (Berman, 2011). However, these often fail or fall short of expectations because the introduced breed is unable to thrive under local conditions or fails to deliver acceptable appearance traits. Therefore, breeds of animals in production systems should be selected on the basis of their superior performance in the local/regional environment and with consideration to local preferences as well as facility, personnel (management) and feed resources.

The trend in recent years has been to take a crossbreeding approach using non-adapted breeds crossed with indigenous breeds (Berman, 2011; Banda *et al.*, 2011) or to use indigenous breeds in the context of a nucleus flock or village-based selection programme to accelerate genetic progress. This trend should be encouraged and expanded. Although this can result in slower gains in production efficiency, it is more effective in ensuring that crossbred animals have the needed survival traits (Funk, 2006; Bee *et al.*, 2006) and that animals possess the culturally appropriate appearance traits.

For example, Mirkena *et al.* (2011) describe an approach where numerous small flocks in a village were treated as one large population, and selection for breeding males was made from that larger group. In other cases governments, NGO or academic institutions can establish nucleus flocks for distribution of high quality genetics. Using these approaches has yielded, for example, significant gains in both lambs born and weaned per ewe (Mirkena *et al.*, 2011). The authors of that study concluded that while this approach held promise to improving production efficiency, it relied on accurate pedigree and performance information and a commitment of continuing support for the programme.

In many countries, including many developed countries, pure-breeding is used extensively (e.g. Holstein and Angus in the United States). While pure-breeding can accomplish goals for genetic improvement and provide the necessary founder animals for effective crossbreeding programmes, there must be careful attention to breeding strategies to minimize inbreeding and incorporate fertility measures into selection indices. During the past decade, selection indexes for Holsteins in the United States have increased emphasis on fertility measures [daughter pregnancy rate (DPR) and productive life (PL)] with evidence of success[69].

It is encouraging to note that regions that have consistently included fertility in selection indexes have not seen the same declines in fertility while achieving substantial gains in production (Berglund, 2008). While this can be accomplished in developed countries, it is more difficult in developing countries where availability of breeding animals of the introduced breed may be limited, pedigree information is incomplete or absent and the cost of genetic analysis is often prohibitive. Increasing emphasis on fertility and productive life in selection indexes will reduce animal numbers needed to produce a unit of product.

Inbreeding-induced reduction in fertility is also an issue associated with pure-breeding. The wide spread use of North American dairy genetics has resulted in a global increase in inbreeding coefficients among major breeds (Funk, 2006). Greater emphasis should be given to reducing inbreeding, particularly in developing countries where knowledge of

---

[69] See Kuhn *et al.* (2006); VanRaden *et al.* (2007); and Norman *et al.* (2009).

inbreeding depression is lower. While pedigree driven mate selection is a common practice to reduce inbreeding in developed countries, this is not the case for many developing countries. For example, in sheep production in Ethiopia, it was reported that approximately 75 percent of farmers replaced their breeding ram from their own flock (Getachew *et al.*, 2011). Similar observations have been made in Buhtan, Nepal, India and China where smallholder Yak farmers select replacement males from their own sires and utilize the same male even as his own daughters reach breeding age (Zi, 2003). Education and temporary mixing of flocks/herds are low input strategies to reduce the negative effects of inbreeding on fertility and should be strongly encouraged.

Early puberty attainment and seasonality

Reproductive efficiency can be improved if animals are managed to achieve puberty early. This can be accomplished through genetic selection (Nogueira, 2004; Fortes *et al.*, 2011), improved metabolic status (Funston *et al.*, 2012), and manipulation of season of birth (Luna-Nevarez *et al.*, 2010; Fortes *et al.*, 2011).

The result of these strategies is to allow for insemination and first parturition to occur at a younger age. For example, under conditions of adequate nutrition, swine should be inseminated on their pubertal estrus to maximize lifetime productivity (Kirkwood and Thacker, 1992). This results in an early economic return on investment and enhanced profitability, more rapid introduction of improved genetics into herd/flocks, and more pregnancies during the animals' productive life (Place and Mitloehner, 2010). However, primary factors limiting this approach are the ability to meet the nutritional needs of growth and gestation during the first parity, and management skills of farm personnel.

Reduction in (or alteration of) seasonality provides opportunities to produce offspring for market during times when prices are highest. In addition, for sheep and goats, it opens up the possibility of obtaining two lambings/kiddings in one year, effectively doubling production per female (Notter, 2008). However, these types of accelerated lambing systems require intensive management (e.g. light control), early weaning, and optimal nutrition.

The effects of season on fertility have also been demonstrated in cattle (De Rensis and Scaramuzzi, 2003), buffalo (Perera, 2011), and swine (Kirkwood and Aherne, 1985). Strategies to address seasonality in these species (especially buffalo and cattle) include increasing metabolic status and reducing heat stress by provision of adequate shade and access to water.

Enhanced fecundity

Prolific breeds/strains of animals can greatly increase the efficiency of production by increasing the number of animals (or live animal weight) weaned per female for each gestation. However, breed choice must meet the requirements outlined above for appearance traits, adaptation to regional climate, feed and production/management practices (Getachew *et al.*, 2011). This approach is less relevant to cattle production because twins are generally not favoured due to the resulting increase in periparturient problems (dystocia, uterine infection, delayed resumption of cyclicity).

Several sheep breeds exist (e.g. Finnsheep, Romanov, Boorola Merino, etc.) that exhibit increased ovulation rate and litter sizes. In addition, standard gene introgression (mating) strategies have been used to improve fecundity in existing breeds without loss of desired breed characteristics and appearance traits (Notter, 2008). For example, the unimproved version of the widely utilized Awassi and Assaf breeds (fat tail sheep) in the Middle East have been introgressed with the Boorola Merino fecundity gene (FecB gene) resulting in the Afec Awassi and Afec Assaf breeds that exhibit a yearly increase of approximately one additional lamb per ewe (Gootwine, 2011).

A similar approach using the fecund Indian Garole breed crossed with the Laland strain of the Deccani breed on the Deccani plateau in India resulted in a 33 percent increase in productivity of ewes carrying the FecB gene (FAO, 2011a). However, it is important to note that success of this programme was dependent on additional support for the smallholder farmers, including training in lamb management, veterinary care and insurance payments.

The FecB gene mutation is also present in a number of other Asian breeds including the Javanese Thin Tail and Chinese Hu and Han breeds (Notter, 2008). This presents an opportunity for use of these breeds in regional crossbreeding programmes aimed at increasing fecundity. Crossbreeding/gene introgression programmes utilizing prolific breeds have proven their ability to increase fecundity and live weight of offspring weaned per female for each gestation.

Nutritional flushing

The provision of additional dietary energy at the onset of the breeding season (nutritional flushing) and introduction of males (male effect) are strategies to induce the onset of cyclicity early in the breeding season; they have been successfully used to increase ovulation rate in small ruminants (Fitz-Rodriguez *et al.*, 2009; Talafha and Ababneh, 2011).

This can be accomplished in low input agriculture by managing exposure of females to males, by holding some higher quality pasture in reserve to be used at the onset of the breeding season, or by provision of grain for the first two-three weeks of the breeding season. With such nutritional strategies, improvements in ovulation rate of 0.5 to 1 have been reported (Naqvi *et al*., 2012).

In our experience, the combined use of early introduction of males and flushing has been effective in increasing the number of females conceiving early in the breeding season. However, effects reported by others have been variable (De Santiago-Miramontes *et al*., 2011). These strategies are most effective when the animals are not already in good body condition (e.g. are thin).

Early weaning

To maintain a yearly calving interval, beef cows must rebreed within approximately 85 days of parturition. The suckling stimulus can delay or completely suppress cyclicity in beef females, especially when nutrition is inadequate (Crowe, 2008). Suckling-induced anestrus is thought to result from direct endocrine suppression induced by suckling and the increased metabolic demands of lactation.

In systems with sufficient feed and management resources, early weaning is an effective method for induction of cyclicity and rebreeding (Zi, 2003; Crowe, 2008). In management systems that cannot support early weaning, intermittent weaning can be utilized. For example, 12 hour temporary weaning of *Bos indicus* cattle improved conception rates in extensively managed cows (Escrivão *et al.*, 2009).

To maximize fertility in swine production, females should achieve puberty at an early age, be inseminated with high quality semen at their pubertal estrus, farrow a large litter, lactate for three-four weeks, wean that litter and then return to estrus and be rebred within four-eight days (Kirkwood and Thacker, 1992).

Enhanced periparturient care and health

There is a clear positive relationship between health and fertility in farm animals (Weigel, 2006), and the time of greatest risk for disease for any female animal is during the periparturient period[70]. Postpartum disease results in delayed resumption of ovarian activity and longer days between births resulting in poor fertility (Thatcher *et al.*, 2006). Indeed, low fertility accounts for roughly one-third of the voluntary culling decisions in North American dairy production[71].

Successfully navigating the transition period in dairy cows involves careful attention to the metabolic status of cows in the pre- and postpartum period. The length of the dry period could be reduced to less than 60 days and, in fact, recent work suggests a dry period of 30 days may result in better metabolic profiles and reproductive health in the postpartum period (Gumen *et al.*, 2011). However, difficulties that arise in managing cows with little to no dry period may limit the application of this strategy.

Another strategy to optimize metabolic function during the dry period is to increase the roughage content while simultaneously reducing energy in the diet (Beever, 2006). This results in increased DMI and fewer metabolic problems during early lactation. In developed countries, manipulating the composition of dietary fats has yielded improved reproductive performance. For example, current recommendations are to feed a diet enriched in omega-6 fats (pro-inflammatory) in the immediate peripartum period and then switching to omega-3 fats (anti-inflammatory) at 30 days post-partum to promote pregnancy establishment (Thatcher *et al.*, 2006; Silvestre *et al.*, 2011). In addition, genetic selection for resistance to diseases and metabolic disorders should yield improvements in health during the periparturient period (Weigel, 2006).

Health of animals is affected by many aspects of the production system, in particular nutrition, stress, facilities and preventive health measures (vaccination and quarantine of new arrivals). For optimal fertility, dams should receive additional care and optimal nutrition during the period immediately prior to and after parturition. Animals should be vaccinated and receive appropriate boosters for endemic diseases, especially diseases that can cause early embryonic mortality and abortion.

Animals that are diagnosed with disease should receive prompt medical care; however, this is not always the case. In smallholder dairy farms in Malawi, 11 percent of farmers reported that they did not treat sick cows due to lack of available drugs or the high cost of drugs (Banda *et al.*, 2011). Failure to effectively control disease is exacerbated by poor recordkeeping and lack of post-mortem disease diagnosis in developing countries.

---

[70] See Beever (2006); Thatcher *et al.* (2006); and Gumen *et al.* (2011).

[71] See Beever (2006); Thatcher *et al.* (2006); and Gumen *et al.* (2011).

Reduction of stressors

Environmental stressors (heat, transport, predation, feed and water contamination, etc.) have been shown to cause embryo loss, especially in the first four-six weeks after mating/insemination (Hansen and Block, 2004). Management strategies should target reduced stress during early gestation. Special attention should be given to provision of adequate access to shade and water to reduce heat stress and to minimize transport or herding of animals over long distances during the first four-six weeks of gestation.

Assisted reproductive technologies

Artificial insemination and other reproductive technologies (estrus synchronization, embryo transfer, gender-selected semen; DeVries *et al.*, 2008) can be used to enhance the genetic value of offspring, particularly relative to fertility traits.

For example, AI was shown to improve several measures of fertility compared to natural mating when implemented as a programme to improve the efficiency of smallholder swine production in Thailand (Visalvethaya *et al.*, 2011). In addition, 55 percent of smallholder dairy farmers in Malawi reported utilizing AI (Banda *et al.*, 2011). However, success of AI programmes was dependent on distance from access to semen, good quality equipment, training of inseminators, heat detection skills and general education level, and even age of the farmer. These results suggest the potential for improvement in fertility with enhanced educational efforts and small investments in the AI infrastructure.

Hormonal injection programmes designed to synchronize estrus or ovulation are credited, in part, with the apparent reversal of declining fertility seen in North American dairy system during the last decade. These programmes have aided larger farms in dealing with the difficulty of accurately detecting estrus in cattle. The result has been more cows submitted for insemination and higher pregnancy rates (Gumen *et al.*, 2011). Use of these technologies is limited in small ruminants due to their cost, especially in developing countries.

Reproductive management protocols for optimal fertility must include timely and accurate determination of pregnancy status so that decisions can be implemented to cull or re-inseminate females. A minority of smallholder farmers in Malawi (23 percent) reported using pregnancy diagnosis, but this generally occurred 90 days after insemination, precluding the timely re-insemination of cows that failed to conceive (Banda *et al.*, 2011). The typical method was transrectal palpation, but other widely used methods for determination of pregnancy status included failure to return to estrus and physical appearance. These latter two approaches are associated with large errors, particularly if farmers have few cows and they are housed individually (non-grazed) as is often the case.

There should be increased training and encouragement of farmers to conduct transrectal palpation in cattle earlier (days 35 to 45) after insemination as a strategy to reduce calving intervals. Individually-housed animals will present difficulties for visual estrous detection.

SPECIES SUMMARIES BY MANAGEMENT SYSTEM

Improving the nutritional status of any species will improve fertility measures. In general, better nutrition will result in more eggs ovulated, less embryonic mortality, fewer problems in the periparturient period, more rapid return to cyclicity following parturition and earlier attainment of puberty. Adequate nutrition is the foundation for optimal reproductive performance.

Small ruminants (sheep and goats): Can be intensively and extensively managed. Species are heavily utilized in developing countries where management is extensive and facilities, feed and management are of lower quality.

Greatest potential for fertility improvement:

- Low input: Breed choice (including cross-breeding and reduction in inbreeding), twinning, dietary flushing with pasture or concentrates, use of male effect to induce female cyclicity, early weaning (Chanvallon *et al.*, 2010).
- High input: AI, seasonality reduction, early weaning/puberty, genetic selection for fertility, pregnancy tests (chemical or ultrasonic based) for early detection of pregnancy status.

Cattle (dairy): Mostly intensively managed, but also grazed and seasonal. Heavily utilized in developed countries where management is intensive and facilities, feed and management are of higher quality.

Greatest potential for fertility improvement:

- Low input: Breed choice, including crossbreeding (Bee *et al.*, 2006) and reduction in inbreeding, feeding strategy, reduction in stressors, early weaning calves.
- High input: AI, heat detection aids, estrous synchronization, gender-selected semen, embryo transfer, chemical pregnancy tests, early puberty/breeding, increased longevity, genetic/genomic selection for fertility.

Cattle (beef): Mostly extensively managed in cow/calf systems, and intensively managed for finishing in feedlots in developed countries; more finishing on pasture in developing countries. Primary (80 percent) GHG contributions come from the cow/calf phase of the production system. Some impacts from deforestation for expanding pastures for grazing; however, this trend is downward. Heavily utilized in developed countries where management is intensive and facilities, feed and management are of higher quality.

Greatest potential for fertility improvement:

- Low input: Breed choice, including cross-breeding (Bee *et al.*, 2006), reduction in inbreeding, reduction in stressors (environmental, disease), early/temporary weaning calves, induction of early puberty.
- High input: AI, heat detection aids, estrous synchronization, gender-selected semen, embryo transfer, pregnancy tests (chemical or ultrasonic based), early puberty/breeding, increased longevity, genetic/genomic selection for fertility.

Cattle/Buffalo (tri-purpose: meat, milk and draught): Mostly extensively managed or smallholder farms. Heavily utilized in developing countries where management is extensive, and facilities, feed and management are of lower quality.

Greatest potential for fertility improvement:

- Low input: Breed choice, including cross-breeding (Bee *et al.*, 2006), reduction in inbreeding, feeding strategy, reduction in stressors (environmental, disease), early/temporary weaning calves.
- High input: AI, gender-selected semen, embryo transfer, early puberty/breeding, increased longevity, genetic selection for fertility.

Swine: Mostly intensively managed, but many smallholder farms in developing countries.

Greatest potential for fertility improvement:

- Low input: breed choice, including cross-breeding and reduction of inbreeding, reduced piglet mortality, early weaning piglets.

- High input: AI, genetic/genomic selection for productivity traits (fertility, litter size, disease resistance, seasonality, longevity).

Many of the technologies mentioned above are well-established and could be implemented with little or only modest investments in infrastructure and education (e.g. enhanced use of crossbreeding and reduction of inbreeding). It will be important for efforts to include development of value added markets to offset additional costs associated with adoption of these technologies.

Other strategies (estrous/ovulation synchronization, embryo transfer, gender selected semen) require well-developed animal production systems with modern management protocols that are permissive to improved fertility (facilities, nutrition, vaccination, animal welfare). Some of the more effective strategies identified here for developed countries included selection and crossbreeding strategies to return conception rates in dairy cows to levels in the 1990s (about a 5 percent increase) and increase longevity while maintaining current levels of milk production. This would result in a large decrease in the number of replacement animals kept in the herd and cows that are spending more time in the most productive portions on their lactation curve.

Additional opportunities were identified for improvements in both litter size and piglets weaned per litter in China and other Asian countries to levels closer to those achieved in North America. This is estimated to reduce the sow herd in China by up to 2.5 million animals at current production levels. Effective use of breed/strains of small ruminants exhibiting increase ovulation rates has already been demonstrated to result in between 0.5 and 1.0 additional offspring weaned per ewe. In many cases, indigenous fecund breeds exist, thus obviating the need to bring in non-adapted breeds.

Real promise exists for improving production efficiency and thereby reducing GHG production through the adoption of AI and the use of nucleus flock/village-based selection practices in developing countries (Mirkena *et al.*, 2011; Gizaw *et al.*, 2011). There are numerous examples where this has been implemented with some success. This is an area where governments, NGO and academic institutions can have a large positive impact. However, improved fertility must be accompanied with proper nutrition, there must be strong local farmer involvement, assistance in market development and a commitment to continued engagement for these efforts to take root.

Finally, more timely pregnancy diagnosis would result in more services over shorter intervals that will improve pregnancy rates. In large ruminants, transrectal palpation, when practised by an appropriately trained technician or farm worker, would be an effective and low cost method to diagnose pregnancy status and facilitate timely rebreeding. Together, these strategies will reduce the number of animals needed per unit of product produced while at the same time improving profitability of the animal production system.

> *Pursuing a suite of intensive and extensive reproductive management technologies provides a significant opportunity to reduce GHG emissions. Recommended approaches will differ by region and species but will target increasing conception rates in dairy, beef and buffalo, increasing fecundity in swine and small ruminants, and reducing embryo mortality in all species. The result will be less replacement animals needed, fewer males required where AI is adopted, longer productive life and higher production per breeding animal.*

Interactions among mitigation practices

Interactions among animal, environment, management, production, and CH_4 and N_2O mitigation practices are inevitable and as a consequence, evaluation of mitigation practices in controlled experimental conditions often results in unexpected outcomes when applied to the whole farm. Moreover, these interactions within the livestock production system may hinder or enhance GHG mitigation and animal productivity.

While the effects of GHG mitigation practices may be clear for some emission sources at specific stages of the production cycle, the system-wide effects of these practices are often difficult to measure. Furthermore, mitigation practices are not usually mutually exclusive[72].

A hypothetical example of how mitigation practices may have a cumulative effect in decreasing GHG emissions from a dairy production system has been given by Eckard *et al.* (2010). In their example, improved feed conversion efficiency through breeding (10 percent less CH_4 when applied alone), feeding of dietary lipids (10 percent less CH_4 when applied alone), extended lactation management system (10 percent less CH_4 when applied alone) and use of a nitrification inhibitor on the paddocks twice a year (61 percent less N_2O when applied alone), could result in a cumulative reduction of 40 percent in whole-farm GHG emissions (versus 91 percent, if considered to be mutually exclusive and/or additive).

INTERACTIONS IN THE RUMEN

Based on growing awareness of ruminal ecology and fermentation, we should expect interactions in enteric CH_4 production to become increasingly apparent as a result of different dietary or animal conditions. In recent years, considerable research efforts around the world have been funded to elucidate potential animal and microbial genetic variability related to efficiency of feed utilization and enteric CH_4 production.

Among-animal variability is a fact (Martin *et al.*, 2010a) and might be related to microbial inoculation immediately after birth (Yáñez-Ruiz *et al.*, 2010) and therefore amenable to manipulation. Interactions among ruminal microbial communities are complex and have evolved over millennia; successful mitigation of enteric CH_4 is not possible without understanding these interactions, cross-feeding among species, substrate competition and particularly H_2 kinetics, which, according to some, is the key to CH_4 formation and mitigation [see, for example, Janssen (2010)].

Protozoal-methanogen relationships

Protozoal-methanogen relationships are a typical example of interactions related to CH_4 production in the rumen. Protozoa suppression should decrease methanogenesis because

---

[72] Table A5 (see Appendix 2) summarizes interactions among mitigation practices discussed by FAO experts and the authors of this document.

they dispose of 2H through production of H_2 and formate in pathways that include hydrogenosome-bound enzymes (Morgavi *et al.*, 2010; Ushida, 2010). Many researchers have focused on the endosymbiotic methanogens, but the protozoa-associated methanogens actually might be far more represented by ectosymbionts that chemotactically swarm to the surface of protozoa, especially when H_2 production increases after feeding (Firkins and Yu, 2006; Ushida, 2010).

After H_2 production slows down and $[H_2(aq)]$ concentration decreases, these methanogens could detach and then use H_2 derived from other sources such as bacteria adherent to fibrous particles. Isotrichid protozoa sink rapidly to the ventral rumen and reticulum rapidly after feeding, whereas the entodiniomorphid protozoa are highly predominant on standard beef or dairy diets that include considerable amounts of grain (Firkins and Yu, 2006). Although these entodiniomorphid populations are often thought to attach to feed, physical attachment is rarely observed (Firkins *et al.*, 2007). The Jansen (2010) model explains that slower ruminal passage rate will slow the growth rate needed for methanogens to maintain their density in the rumen and increase the total H_2 (and therefore CH_4) produced compared with the faster rate of fluid passage.

Protozoal density is often positively correlated to CH_4 production[73], but several studies have found little relationship between methanogenesis with either protozoal density[74] or even methanogen density[75]. Part of the explanation could be that removal of protozoa provides a void that is taken up by other bacteria many of which also produce H_2. If H_2-producing bacteria are also decreased simultaneously with protozoa by CH_4 mitigation strategies such as unsaturated fat (Yang *et al.*, 2009), CH_4 mitigation cannot be attributed solely to the removal of protozoa. In contrast with that report, defaunation increased the relative abundance of ruminococci, but methanogenesis varied with the time after defaunation (Mosoni *et al.*, 2011). Those authors explained that protozoa might preferentially predate cellulolytic bacteria; however, the interaction is probably more complicated because surface area of fibre, not abundance of cellulolytic bacteria *per se*, limits fibre digestibility (Dehority and Tirabasso, 1998; Fields *et al.*, 2000), and cellulolytic bacteria are firmly adherent. Protozoa also have positive benefits that might enhance fibre digestibility on a net basis (Firkins and Yu, 2006).

Methanogenesis independent of protozoa in the hindgut can be as high as 20 percent of total CH_4 production from calves (Schönhusen *et al.*, 2003). The proportion of fibre digestibility occurring in the hindgut of dairy cattle has been questioned (Huhtanen *et al.*, 2010), although hindgut capacity seems significant (Gressley *et al.*, 2011) and might be shifted more when stringent CH_4 abatement strategies such as coconut oil are utilized (Reveneau *et al.*, 2012). The proportion of hindgut NDF digestibility might be greater with some diets, particularly when non-forage fibre sources are combined in low forage diets (Pereira and Armentano, 2000).

Insufficient particle size of forage, particularly in high concentrate diets, can decrease ruminal pH (Yang and Beauchemin, 2009) and presumably methanogenesis. Moreover, Firkins *et al.* (2001) found that increasing starch digestibility in the rumen through finer grind-

---

[73] See Morgavi *et al.*(2010); and Patra (2010).

[74] See Hristov *et al.* (2011b); and Morgavi *et al.* (2011).

[75] See Firkins and Yu (2006); and Mosoni *et al.* (2011).

ing of corn grain was partially offset by decreasing NDF digestibility and did not increase microbial protein production, apparently because of decreased efficiency of microbial protein synthesis. Yet, finer grinding of corn also helps to maximize total tract digestibility of starch. These inverse responses between starch and NDF digestibilities can be exacerbated by type of endosperm (Lopes *et al.*, 2009). Buffering capacity in the lower digestive tract is much less than in the rumen, so hindgut acidosis is a potential problem with increased passage of digestible substrate (Gressley *et al.*, 2011). Consequently, methanogenesis would be expected to be very low in the hindgut as pH drops below 6.0.

Although variation in site of digestion might complicate prediction of methanogenesis per animal in a systems approach, it also complicates prediction of N excretion and animal productivity. Substrate reaching the fermentative sites within the intestines could trap more N in faeces rather than in urine because of either blood urea-N cycling and bacterial assimilation or perhaps because of decreased protein digestibility (Pereira and Armentano, 2000; Gressley *et al.*, 2011). Shifting starch digestion to the small intestine (including some escaping the animal's digestion) increases tissue N retention, which should decrease N excreted in urine (Reynolds *et al.*, 2001) and the potential of N_2O emission from manure application. The latter study documented that even abomasal infusion of starch can depress milk fat synthesis.

The combination with fat in higher concentrate diets increases likelihood for decreased CH_4 production but also presents the opportunity for shifting digestion to the hindgut. Meta analyses are improving our ability to integrate rumen-degraded starch, effective NDF, DMI and their interactions (Zebeli *et al.*, 2010), but such comprehensive meta approaches have not been done to assess dietary fat's effects on site of carbohydrate or protein digestion.

Previous efforts to scale CH_4 suppression to DMI will inflate potential benefit for dietary fats for a number of reasons. Unsaturated and medium-chain saturated FA, which are more bioactive against methanogens and protozoa (Hristov *et al.*, 2004; Firkins *et al.*, 2007), are also more likely to decrease DMI (Allen *et al.*, 2009; Lee *et al.*, 2011a). Although net energy intake might not be decreased, the fermentable portion of the diet would be decreased (Martin *et al.*, 2010a). This response would be exacerbated if fibre digestibility in the rumen was decreased or digestion shifted to the hindgut. In addition, if intake was suppressed enough to depress productivity, then more dairy cattle or more days on feed would be needed to maintain the same level of herd milk or meat production (Firkins, 2010; Hollmann *et al.*, 2012).

There are numerous opportunities to simultaneously decrease wastage of N and methanogenesis in the rumen. For example, selecting or harvesting forages with higher sugar concentrations (see *Forage quality and management*) or decreased likelihood of ruminal proteolysis can help trap more dietary N as microbial N (Kingston-Smith *et al.*, 2010). Besides plant proteases still remaining active in grazed forage, the authors explained that AA-fermenting bacteria might be stimulated when forages have excess rumen-degraded protein. These bacteria must flux through a rapid number of AA per unit of time, because ATP yield per AA is low in a similar way that methanogens have a relatively low ATP yield per mole of CH_4 produced (and, with four moles of H_2 needed per mole of CH_4, must flux rapidly through H_2). Feeding glucose decreased NH_3 irreversible loss, but the response appeared to be a result of decreased proteolysis rather than from

NH_3 assimilation (Hristov *et al.*, 2005), perhaps because sugar-using bacteria compete for AA with the obligate AA fermenters (Firkins, 2010).

Suppressing both methanogens and obligate AA fermenters presents common opportunities for control because a relatively small decrease in number of cells can have a large response in activity and response on methanogenesis or N excretion (and ultimately N_2O production). Branched chain AA degradation by mixed rumen microbes is linked with disposal of reducing equivalents and methanogenesis (Hino and Russell, 1985). Essential oils inhibit both methanogens and the obligate AA fermenters (Eschenlauer *et al.*, 2002). In contrast with essential oils, polyunsaturated FA depress cellulolytic bacteria but increase proteolytics (Yang *et al.*, 2009).

These types of studies are helpful, but more work needs to target the obligate AA fermenters *in vivo* using quantitative molecular techniques because moderate depressions in this high-activity, low-abundance group might be masked when using cultivation-based assays such as in the Yang *et al.* (2009) study. Many researchers have focused on combined inhibition of protozoa and methanogens because of their strong association in interspecies H_2 transfer plus protozoal-mediated intraruminal N recycling (Firkins *et al.*, 2007). However, some approaches probably magnify this linkage because deaminase activity of protozoa is probably inflated by using disrupted cells (Forsberg *et al.*, 1984), and the decrease in NH_3 concentration with defaunation must be due, at least in part, to protozoa not using NH_3 for protein assimilation (Firkins *et al.*, 2007) as would bacteria taking up the void left by displaced protozoa.

N retention and CH_4 emissions

Forage source and quality have several potential interactions that influence the efficiency of dietary protein capture or possibly CH_4 mitigation strategies. These strategies must be scaled per unit of retained N (or average daily gain) or ECM because different forage sources can influence bulk fill-regulated voluntary feed intake. Legumes can capture N_2 from the atmosphere, but spreading more manure N beyond uptake by the leguminous plant can decrease N_2 fixation and increase N_2O volatilization from soil to atmosphere (Kingston-Smith *et al.*, 2010).

To avoid this loop between excessive N excretion by the animal and excessive N fertilization when the forage is based on legumes, one simple approach would be to plan for increased DMI compared with grasses; higher intake allows rations to be formulated with a lower percentage of protein to meet the animal's MP requirements on a gram/day basis (Voelker Linton and Allen, 2009). Better quality legume silages could enhance this intake response, so lowering the dietary protein percentage should have a greater opportunity for trapping dietary N into milk protein if rumen-undegradable methionine sources are fed (Broderick and Muck, 2009).

Increasing the proportion of forage from alfalfa silage (replacing corn silage) has been found to increase DMI (Weiss *et al.*, 2009a), but increasing alfalfa silage:corn silage increased excretion of urinary N. The authors emphasized the over-sensitivity of the NRC (2001) MP model (it over-predicts the decrease in MP-allowable milk with insufficient MP supply), which emphasizes the priority for improving accuracy and precision of MP models. The companion study (Weiss *et al.*, 2009b) documented that MP from that model was optimized at about

11 percent of dry matter and that manure NH_3 production was least with increasing alfalfa silage or increasing starch appropriately. The latter response illustrates the need to better account for digestible starch supply and its site of digestion with differing forages, especially because corn silage supplies a significant proportion of starch in many dairy rations.

Feeding brown mid-rib (BMR) corn silage (characterized with lower lignin content and greater NDF digestibility) often increases DMI compared with conventional hybrids. However, if intake is not increased corresponding with increased fibre digestibility from BMR silage, then more MP is needed to match with the extra energy supply (Weiss and Wyatt, 2006). These authors commented that increasing MP tended to increase DMI, which would increase intake of rumen-digestible OM in the rumen to increase microbial protein synthesis and capture of N. In this case, the extra MP was associated with increased excretion of N, documenting the need to better formulate for metabolizable AA profile in lower protein diets and to ensure that rumen-degraded protein supply does not limit microbial protein synthesis with improving forage quality.

Research findings related to enteric CH_4 mitigation strategies need to be transferred into practice with some caution. There is greater variability in farm situations than in controlled research, and dietary intervention could decrease CH_4 or N excretion per cow but have no net gain when applied to a system (St-Pierre and Thraen, 1999), particularly because fewer cows and their replacements are needed to produce the same milk within a milk marketing region (Capper *et al.*, 2009). Managerial decisions to increase fibre digestibility would equate to greater VFA (and CH_4) production, as shown for exogenous enzymes (Zhou *et al.*, 2011b), but if CH_4 was increased less than digestibility was increased, there still could be a direct advantage in a systems approach.

Interactions among ruminal microbial communities are complex and have evolved over millennia. Successful mitigation of enteric CH_4 is not possible without understanding these interactions, cross-feeding among species, substrate competition and H_2 kinetics. A classic example of species interactions in CH_4 formation is protozoa-methanogen interactions, although studies have found little relationship between methanogenesis and protozoal density. Carbohydrate degradation is directly related to CH_4 production but interactions in carbohydrate digestion involve source (structural vs non-structural), ruminal pH, dietary protein composition and N availability in the rumen, and extent of ruminal escape and site of carbohydrate digestion, with the latter two categories also impacting N utilization and potentially N_2O emissions from soil. Enteric CH_4 mitigation effects documented in controlled animal experiments have to be interpreted with caution and may not replicate in practical farm conditions due to various whole-farm interactions.

INTERACTIONS AMONG FEED ADDITIVES, RATION, ENTERIC CH_4 AND ANIMAL PRODUCTIVITY

Feed additives and dietary manipulations targeting enteric CH_4 reduction are mostly studied in isolation[76], but can have synergistic or antagonistic effects. It is unlikely that mitigation practices reviewed under *Enteric Fermentation* can have additive effects on

---

[76] Very few *in vivo* experiments have studied synergy/antagonism among mitigating agents.

enteric CH_4, but there is not much evidence to support or refute this assumption. It is also unlikely that CH_4 inhibitors can have an additive effect because the rumen ecosystem has a limit to how much imbalance can be tolerated before feed intake, digestibility and animal production are negatively affected.

On the other hand, dietary manipulation targeting increased nutrient digestibility, for example, is expected to decrease enteric CH_4 production per unit of product and would most likely decrease GHG emissions from stored manure because less fermentable OM will be excreted with faeces. Dietary manipulations resulting in increased feed intake, digestibility and improved animal productivity would result in reduced enteric CH_4 production per unit of product. Stable rumen fermentation (in terms of pH) might improve animal health[77] and feed efficiency, and reduce GHG Ei by the animal or from manure storage (due to excretion of less fermentable OM with faeces).

Nitrates are an example of a possible interaction between feed additives and manure N emissions. Enough nitrates must be fed to pull dissolved H_2 away from methanogenesis, which means that reduction of nitrates to NH_3 could increase NH_3 absorbed from the rumen and urea excreted in urine – assuming that nitrite accumulation, absorption and methemoglobin production is not a negative factor (van Zijderveld *et al.*, 2011b). In the latter study, the major dietary ingredient was corn silage (53 percent of total diet DM) with a protein concentration of 74 g/kg DM, and the authors used formaldehyde-treated soybean meal (11 percent of total diet DM). However, the effective nitrate dose to inhibit methanogenesis without increasing loss of labile N in urine could be a complicating factor, particularly for forages that already have a high non-protein N concentration such as low-DM alfalfa silage (Messman *et al.*, 1994; Hristov *et al.*, 2001) or grasses heavily fertilized with N (Fievez *et al.*, 2001b). Feeding hay with increasing forage N concentration through fertilization in high forage diets improved N retention, but total dietary protein concentration was low (Messman *et al.*, 1992).

When adopting mitigating practices related to animal nutrition, it must be borne in mind that diets are formulated to make up 100 percent of DMI and decreasing concentration of one nutrient will lead to increasing the concentration of another. An example was given earlier with dietary protein. Decreasing dietary protein concentration to address NH_3 and N_2O losses from stored manure or manure-amended soil may increase enteric CH_4 emission, as shown by the modelling effort by Dijkstra *et al.* (2011b). Given that there is not much experimental evidence that such an intervention will in fact increase enteric CH_4 emissions, reduction of dietary protein is still an important and recommended NH_3 and N_2O mitigation option. Reducing N intake should not be done at the expense of decreasing N availability for ruminal microbes. Maintaining optimal conditions for fibre degradability in the rumen is a primary goal of ruminant nutrition and has many benefits related to animal health, farm profitability, and also mitigation of GHG Ei.

Feeding dietary lipids and increasing the concentrate feeds in the diet is another area that may have implications in manure GHG emissions and overall whole-farm C footprint. There is a substantial body of evidence that lipids can decrease CH_4 production in the rumen. The effect could come both from direct inhibition of rumen methanogenesis and from replacing part of the dietary carbohydrates (when included, lipids usually replace

---

[77] This is perhaps one reason why Cottle *et al.* (2011) listed rumen buffers among mitigation options.

concentrates), which are the primary substrates that lead to CH_4 formation. However, the risk with lipids lies in the potential negative effect on feed intake and animal production, specifically when total fat in the diet exceeds 5 to 6 percent (DM basis). Feed intake is what drives production in ruminants and any decrease in DMI, particularly in intensive production systems, will lead to decreased milk production or ADG. The effect of FA from vegetable oils, long-chain unsaturated and medium-chain saturated FA on ruminal bacteria, particularly fibrolytic bacteria, are well-documented and need to be considered. Decreased carbohydrate degradability in the rumen and the total digestive tract will result in increased OM in manure and may increase CH_4 emissions during manure storage. Thus, the combination of potential decreases in feed intake and fibre digestibility may counteract the enteric CH_4 mitigating effect of lipids resulting in similar or even increased GHG Ei.

Similar risks can be related to increased concentrate inclusion in the diet. The fact that enteric CH_4 formation decreases with feeding more concentrate is not disputed, but higher starch in the diet may potentially have a destabilizing effect on ruminal fermentation, pH, overall rumen health and nutrient digestibility. If total tract OM digestibility is impaired, due to excessive inclusion of starch in the diet, animal production will decrease and GHG Ei will increase. In addition, manure CH_4 emissions may also increase, due to increase concentration of available substrate, and this will counteract the enteric CH_4 mitigation effect on a whole-farm scale.

It is also not clear at what level of concentrate inclusion enteric CH_4 mitigation takes place. In Table A5 (see Appendix 2) we use the > 35 to 40 percent level proposed by Sauvant and Giger-Reverdin (2009), but as indicated under *Concentrate inclusion*, there are examples in the literature where the effect of increasing concentrate inclusion in the diet on CH_4 production was linear. In many dietary situations, concentrate feeds have a positive impact on animal productivity, which will decrease enteric CH_4 and overall whole-farm GHG Ei. The latter effect also needs to be accounted for when evaluating the mitigating potential of concentrate feeds.

Improving pasture quality in terms of forage digestibility is an efficient way of decreasing GHG emissions from the animal and the amount of manure produced. However, in pasture-based production systems, improving forage quality often means increasing N fertilizer application rates, which can have a significantly negative impact on urinary N losses by the animal and soil N_2O emissions. These counteracting effects have to be carefully evaluated in the context of the whole production system so that pasture and animal productivities are optimized and whole-farm GHG emissions are minimized.

Several important interactions can occur in relation to improving low-quality feeds, primarily in developing countries. For example, if anhydrous NH_3 or urea is used to treat straw and other low-quality feeds, a significant portion (up to 50 percent) of the N applied will likely be lost as NH_3. Although not a GHG, NH_3 has significant environmental implications (see Hristov *et al*., 2011a). Despite these potential losses of N with NH_3, the benefits of increasing digestibility of low-quality feeds through alkaline treatments must be carefully evaluated. Part of the N used in this treatment binds to fibre and can be partially utilized as an N source by ruminal bacteria thus enhancing AA supply to meet animal requirements for production purposes. Strategic supplementation of low-quality feeds has the sole purpose of improving animal performance by supplementing available N for microbial protein synthesis in the rumen and balancing rations for macro- and micro-nutrients. These nutrients may be limiting for feed intake and production and it is expected that their supplementation will increase intake, manure output and GHG emissions from stored manure and after soil application. Emission intensity, however, is expected to decrease.

> *Feed additives and dietary manipulations targeting enteric CH_4 reduction are mostly studied in isolation and very few in vivo experiments have studied synergy/antagonism among mitigating agents. When adopting mitigating practices related to animal nutrition, decreasing concentration of one nutrient will lead to increasing the concentration of another. Thus, decreasing dietary protein may increase concentration of dietary carbohydrates and result in increased CH_4 production. Then, this may be counterbalanced by decreased N_2O emissions when manure is applied to soil. The CH_4 mitigating effects of other dietary interventions such as lipid and concentrate supplementation must be carefully balanced against potential negative impact on fibre digestibility, feed intake and animal productivity. Similarly, the benefits of fertilizer application to enhance pasture yield and quality/digestibility and thus decrease enteric CH_4 Ei have to be evaluated in the context of increased N_2O emissions from soil.*

INTERACTIONS AMONG FEEDING PRACTICES, MANURE STORAGE AND LAND APPLICATION

Most interactions among nutrition of the animal, stored manure handling and land application mitigation practices result from changes in the flow of N and C sources throughout the production system.

Using tannins as a GHG mitigation tool is one example of potential interactions in this category. The implications of supplementing diets with tannins, feeding tanniferous feeds or adding tannins to manure have been extensively discussed under *Plant bioactive compounds*. The main interaction with dietary supplementation of tannins or inclusion in the diet of tanniferous feeds is with manure GHG, particularly N_2O, emissions. Tannins bind to N (in the rumen and the whole digestive tract, or in manure if treated with tannins) and N_2O emissions from manure-amended soil are expected to decrease.

Another mode of action of tannins is through diversion of N excretion from urine to faeces. Urinary N is the primary source of NH_3 and N_2O emissions and decreasing its proportion in manure N is expected to decrease these emissions during manure storage or after soil application. This can be particularly important in grazing systems, where urine patches are the main source of N_2O emission. There are also indications that tannins can reduce CH_4 emissions from stored manure. As pointed out in Table A5 (see Appendix 2), manure that will be fed into an anaerobic digester should not be treated with tannins because this can decrease fermentation rate and CH_4 production.

Nitrous oxide production in soil is the result of microbial transformation of NH_3-N into nitrates and consequent denitrification resulting from changes in the oxidation sites in the environment. Several examples exist of how reducing the pool of NH_3 in soil or manure can reduce potential N_2O emissions[78]. The relationship between manure ammonium (or NH_3) and soil N_2O emission is complex and has been discussed earlier in this document. As pointed out by Petersen and Sommer (2011), if a mitigation technology reduces NH_3 losses from manure, the preserved ammonium N may be later available for increasing soil N_2O emissions.

On the other hand, practices that result in increased NH_3 emissions in general will reduce the overall efficiency of the production system, reduce the amount of N being recycled on the farm, and will result in increased demand for N fertilizer, which could increase GHG emissions. For example, lower N_2O emissions are expected when manure is left on the soil surface compared with when it is incorporated into the soil, largely because a significant portion of the manure N is lost as NH_3 before undergoing nitrification and denitrification. Incorporating manures can greatly reduce NH_3 emissions, leaving more N susceptible to emission as N_2O through nitrification and denitrification. However, reduction in N losses as NH_3 with incorporation means that a smaller quantity of manure is required to provide the crop N requirements and the potential for N_2O production is proportional to the quantity of N applied.

The trade-off between reduced NH_3 volatilization and higher N_2O production may be even greater for incorporation by injection, because the concentration of manure in below-ground bands leads to conditions that can be more conducive to denitrification than with even mixing by tillage (Dell *et al.*, 2011).

Manure acidification or cool manure storage are other effective NH_3 emission mitigation strategies that can also potentially increase N_2O emissions if the greater ammonium content of the manure is not accounted for when determining land application rates. The variability and uncertainty in N_2O emissions is an important aspect when evaluating the effects of mitigation practices that result in opposite effects with respect to NH_3 and N_2O emissions. In this case, N_2O emissions are better treated as potential emissions, because they might or might not occur depending on many factors involved in the nitrification and denitrification processes. On the other hand, NH_3 emission and consequent N loss are most likely to occur, but vary in magnitude due to environmental and management factors.

Reducing dietary N intake results in reduced N excretion with urine and reduced potential for N_2O emissions when stored manure is applied to soil. Studies by Külling *et al.* (2001, 2003) and Velthof *et al.* (2005) have measured the effect of the interaction among dietary N input, manure storage and land application of manure. In general, reduced dietary N input resulted in reduced CH_4 and N_2O emissions, and those reductions were compounded by reductions from manure storage and land application methods.

An interesting and unexpected outcome from the interaction of grazing intensity and N_2O emissions was demonstrated by Wolf *et al.* (2010). In their study, grazing intensity in the autumn in the high plateaus of Tibet prior to seasonal freezing resulted in increased emissions in the following spring freeze-thaw period, because the effect of residual pasture, snow accumulation and soil microbial metabolism resulted in increased microbial activity during the cold months. Increased microbial activity during the winter months promoted OM decomposition and nitrate accumulation, which in the freeze-thaw pro-

---

[78] See Külling *et al.* (2001); Velthof *et al.* (2005); and Lee *et al.* (2012a).

cess of the following spring resulted in short duration high intensity N_2O emission events that accounted for the majority of N_2O emissions of the year. The opposite effect was described in the intensive pasture systems of New Zealand by de Klein *et al.* (2006), where restricted grazing in autumn-winter seasons resulted in reduced overall N_2O emissions by reducing soil N deposition in excreta during the periods in which N_2O emission potential was the highest.

The cycling of N, and the reduction state in which it is present, changes the nature of interactions among mitigation practices. Permeable manure storage covers is an example, in which the intended mitigation practice results in a potential increase of GHG emissions. Depending on its thickness and permeability, nitrification may occur in the upper layers of the cover while, in the lower levels, denitrification conditions may enhance N_2O formation (Nielsen *et al.*, 2010; Hansen *et al.*, 2009). In this case, the interaction of available C and N sources in the correct oxidation form resulted in an effect contrary to that hoped for. A similar interaction results when manure was incorporated in pockets into the soil through injection or shallow ditches. In this case, incorporation of manure greatly reduced NH_3 emission and resulted in reduced N losses and no CH_4 emissions. Nonetheless, the increased OM in manure accelerates soil metabolism, depleting oxygen in the soil porous space, thus triggering denitrification and N_2O emissions. By using anaerobic digestion, or separating manure solids, the organic content of manure is reduced, which generally results in lower emissions of N_2O (Clemens *et al.*, 2006; Velthof and Mosquera, 2011). In general, practices intended to reduce production of CH_4 though aeration or oxidation during manure storage may result in an increased production of N_2O at following processing stages.

Composting presents an interesting case of interactions among GHG mitigation practices. By design, composting increases NH_3 emission and total N losses. The implications of increased NH_3 emissions have been discussed extensively in this document, but the effect of composting on CH_4 and N_2O emissions is complex. Methane production is an anaerobic process and aeration of composted manure will naturally suppress methanogenic activities, but will increase NH_3 and possibly N_2O emissions. Nitrous oxide emissions from compost, however, are generally small. The loss of NH_3 is significant, but technically, this will reduce soil N_2O emissions and thus total non-CO_2 GHG emissions from composted manure, compared with other manure management systems.

Composting requires energy input and this can be counted as GHG debits, but farmers may use compost as animal bedding thus recycling C within the farm and realizing C savings. On a whole-farm scale, composting seems to achieve net emission reduction, compared with other manure storage practices. Composting also has a beneficial odour-mitigating effect, which is in many cases is as important as, if not more important than, GHG in terms of public perception of animal agriculture.

With the increased production and collection of CH_4, anaerobic manure digestion appears to be a very effective means to reduce GHG emissions during storage and N_2O emission following land application, and generate renewable energy. Because anaerobic conditions inhibit nitrification, N_2O production – both through nitrification and subsequent denitrification – should be greatly reduced during digestion. As noted above, the lower OM content can also lead to lower N_2O emissions when digested manure is land applied. However, the inhibition of nitrification under anaerobic conditions can lead to greater ammonium-N in the manure. The greater ammonium concentration of digested manures, coupled with the pH increase that is likely with digestion, can lead to greater NH_3 emissions. Similarly, the use of sealed manure storage with flaring of CH_4 can effectively reduce GHG emission. However, prevention of NH_3 losses during storage can increase the ammonium content of the manure and lead to deferred emission of NH_3 when the manure is land applied.

The use of urease inhibitor has been shown to reduce NH_3 emissions, while 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 use of inhibitors only delaying NH_3 or N_2O emission under some conditions. For example, repeated application of urease inhibitor could be needed to prevent urea decomposition and subsequent NH_3 emissions during prolonged manure storage. As with anaerobic digestion, use of nitrification inhibitors could result in greater NH_3 emission following land application of manure due to greater accumulation of N as ammonium.

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 can have a variable effect on N_2O emission given that soil moisture, temperature and the rate of uptake of ammonium and nitrate by plants strongly influence N_2O emission rates. Application of manures during prolonged periods with wet soil and periods of low plant N uptake are likely to increase N_2O emissions. Manure application to wet or frozen soils can also have negative implications for water quality by increasing the runoff of manure nutrients and pathogens to water bodies (Srinivasan *et al.*, 2006). However, emissions are generally low from extended outdoor manure storage during winter in cool climates. Therefore, a combination of decreased storage times in warm weather and extended winter storage is a viable option in many regions.

In general, the use of cover crops can increase plant N uptake and decrease accumulation of nitrate and reduce N_2O production through denitrification. Interactions among soil conservation and management practices, however, are complex and may easily shift the balance of GHG fluxes. A study from Denmark reported a strong correlation among soil conservation practices, cover cropping and tillage (Petersen *et al.*, 2011). These authors concluded that reduced tillage may be an N_2O mitigation option in rotations with cover crops, but that there was inconclusive evidence that the overall balance of N_2O emissions is positively affected.

Another example of these interactions is the study by Garland *et al.* (2011). These authors demonstrated that differences in cover crop management had the capacity to significantly affect GHG emissions; for example, mowing the cover crop produced larger peak emissions (14.1 g N_2O-N/ha/day; no-till system) compared with cover crop incorporation by disking (1.6 g N_2O-N/ha/day; conventional tillage system). Thus, cover cropping may mitigate GHG, specifically N_2O emissions, under some production systems but have no effect under others.

Finally, manure management technologies can interact with each other and their mitigation potential has to be evaluated in the context of the whole production system. For example, Prapaspongsa *et al.* (2010a,b) compared 14 pig manure management practices based on combinations of thermal pre-treatment, anaerobic digestion, anaerobic co-digestion, liquid/solid separation, drying, incineration and thermal gasification with respect to their energy, nutrient and GHG balances. The anaerobic digestion-based scenario with natural crust storage had the highest GWP reduction because of high efficiencies in energy and nutrient recovery with restricted emissions of GHG and nitrate. The incineration and thermal gasification-based scenarios and the scenario without a treatment system but applying the deep injection method yielded the greatest reduction in respiratory inorganics and terrestrial eutrophication categories because they had the lowest NH_3 emissions. Manure incineration combined with liquid/solid separation and drying of the solids was a promising management option yielding a high potential energy utilization rate and GHG reduction. The authors concluded that the choice of manure management technology has a strong influence on energy, nutrient and GHG balances and that, in order to obtain reliable results, the most representative and up-to-date management technology combined with data representative of the specific area or region has to be considered.

> *In conclusion, it is critical that manure management technologies are examined in the context of the whole production system. Most interactions among animal nutrition, stored manure handling and land application mitigation practices result from changes in the flow of N and C sources throughout the production system. An example of these interactions is the effect of dietary tannins on N digestion and excretion (in urine vs faeces) and* N_2O *emissions from soil. Another example of interactions related to manure management is between* NH_3 *and* N_2O *emissions; if* NH_3 *losses from manure are reduced, there is a chance that* N_2O *emissions may increase when manure is applied to soil. On the other hand, however, practices that result in increased* NH_3 *emissions will reduce the overall efficiency of the production system, reduce the amount of N being recycled on the farm, and increase the demand for N fertilizer. Permeable manure storage covers is another example, in which the intended mitigation practice may result in a potential increase of the overall GHG emissions. Being an anaerobic process,* CH_4 *production may decrease during composting of manure, but* NH_3 *and possibly* N_2O *emissions may increase. Similarly, anaerobic digesters and nitrification inhibitors could result in greater* NH_3 *emissions following land application of manure.*

INTERACTIONS AMONG NUTRITION, ANIMAL HEALTH AND PRODUCTIVITY

The interactions among nutrition, animal health, productivity and GHG are very complex and difficult to assess. Nutrition affects animal health and productivity, resulting in varying CH_4 and N_2O emissions. At the same time, changes in animal health due to disease or parasite challenges translate into metabolic changes such as reduced intake, lower digestibility and increased requirements for maintenance energy that in turn increase GHG Ei.

As discussed by Sykes (1994), the effect of parasites in animal production and health depends on the condition of the animal when the parasitic challenges occur. Animals with poor nutrition and impaired health tend to be less resistant and exhibit a diminished productivity as a result of parasitism compared with animals that are well-nourished and in good health.

Animal health and nutrition can affect CH_4 emissions directly by modification of the rumen metabolic pathways and indirectly by changing N metabolism and utilization and, as a result, the potential for N_2O emission from manure. In addition, animal health and nutrition can affect animal productivity, fertility and mortality, which results in increased or decreased herd size to maintain production, thus affecting whole-farm CH_4 and N_2O emissions. Unrealized animal production, due to carcass condemnation because of diseases and liquidation of animals as a result of zoonotic diseases, results in GHG emissions, unrelated to animal production, that are difficult to quantify. Cases such as foot-and-mouth disease and the avian influenza pandemic resulted in the liquidation of millions of animals and the emission of GHG during their disposal.

Improved nutrition and feed management not only result in absolute CH_4 and N_2O emission reductions, but also increase productivity, nutrient use efficiency and animal health, which can further reduce the amount of GHG Ei (Gerber *et al.*, 2011). The magnitude of the reduction depends on the state of the production systems. Improved nutrition and health conditions in livestock systems in, for example, sub-Saharan Africa could result in gains in productivity and significant reduction in GHG Ei, while similar gains would be difficult to achieve in more intensively managed production systems. Some examples of such interactions are provided in the studies on the benefits of interventions to control tsetse and trypanosomiasis in sub-Saharan Africa (Shaw *et al.*, 2006) and mastitis control in highly intensive dairy production systems (Hospido and Sonnesson, 2005).

> *In conclusion, research findings need to be transferred into practice with caution because of the greater variability in farm situations than in controlled research. Interactions among individual components of livestock production systems are very complex, but must be considered when recommending GHG mitigation practices. 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. Conversely, some mitigation practices are synergistic and are expected to decrease both enteric and manure GHG emissions (for example, improved animal health and animal productivity).*

Appendix 1

Enteric methane prediction equations

EQUATIONS DEVELOPED IN THIS REPORT

CH_4, g/day = 2.54 (4.89) + 19.14 (0.43) × DMI, kg/day

where

CH_4 is enteric methane production (SE in parentheses); DMI is dry matter intake.

Equations for lactating and non-lactating animals (SE in parentheses)

Lactating cows: CH_4 (GE Mcal/day) = 0.37 (0.37) + 0.0392 (0.0015) GEI (Mcal/day) + 0.0189 (0.0077) NDF (percent) – 0.156 (0.034) EE (percent) + 0.0014 (0.0003) BW (kg)

Dry cows: CH_4 (GE Mcal/day) = 0.45 (0.13) + 0.0503 (0.0014) GEI (Mcal/day) – 0.0556 (0.015) EE (percent) + 0.0008 (0.0002) BW (kg)

Heifers and steers: CH_4 (GE Mcal/day) = – 0.056 (0.122) + 0.0447 (0.0028) GEI (Mcal/day) + 0.0039 (0.0018) NDF (percent) – 0.033 (0.019) EE (percent) + 0.00141 (0.00014) BW (kg)

where

Enteric CH_4 is expressed as CH_4 GE, Mcal/day; GEI is gross energy intake, Mcal/day; NDF is neutral-detergent fibre, percent in the diet, DM basis; EE is ether extract, percent in the diet, DM basis; BW is body weight, kg.

EQUATIONS REFERENCED IN THIS REPORT

Equation from Giger-Reverdin and Sauvant (2000)

CH_4 energy as percent of GEI = – 10.5 + 0.192DEI/GEI – 0.0567EE + 0.00651St + 0.00647CP + 0.0111NDF

where

DE, digestible energy; EE, St, CP, and NDF are ether extract, starch, crude protein, and neutral-detergent fibre, g/kg dietary DM.

Equation from Yan *et al.* (2000)

CH_4 energy (MJ/day) = DEI, MJ/day × (0.094 + 0.028 × $\text{silage}_{\text{ADFintake}}/\text{total}_{\text{ADFintake}}$) – 2.453 × (level of intake above maintenance)

CH_4 energy (MJ/day) = DEI, MJ/day × (0.096 + 0.035 × $\text{silage}_{\text{DMI}}/\text{total}_{\text{DMI}}$) – 2.298 × (level of intake above maintenance)

where

DEI is digestible energy intake; ADF is acid-detergent fibre; DMI is dry matter intake.

Equation from Sauvant and Giger-Reverdin (2009)

$Y_m = 10.8 - 2.99 \times LI + 0.40 \times LI^2 + 7.23 \times CPr - 8.71 \times CPr^2 - 0.98 \times CPr \times LI$

where

Y_m is CH_4 energy as a percent of gross energy intake; LI is level of intake as percent of body weight; CPr is the proportion of concentrate in the diet.

Equations from Ramin and Huhtanen (2013)

Equation for predicting the Y_m factor (SE in parentheses)

CH_4-GE (kJ/MJ) = 1.5 (13.7) – 0.70 (0.072) × DMIBW + 0.073 (0.0134) × OMD_m – 0.13 (0.02) × EE) + 0.048 (0.0099) × NDF + 0.045 (0.0096) × NFC (adjusted root mean square error, RMSE, 3.18 kJ/MJ; CV = 5.54 percent)

where

DMIBW is DMI/BW (g/kg), OMD_m is OM digestibility at maintenance level of intake (g/kg), and EE, NDF and NFC are concentrations (g/kg DM) of ether extract, NDF and non-fibre carbohydrates, respectively.

Equation for predicting total CH_4 production (SE in parentheses)

CH_4 (L/day) = 64 (35.0) + 26.0 (1.02) × DMI – 0.61 (0.132) × $DMI^2{}_{\text{(centred)}}$ + 0.25 (0.051) × OMDm – 66.4 (8.22) × EE intake – 45.0 (23.5) × [NFC/(NDF+NDF)] (adjusted RMSE of 21.1 L/day)

where

DMI is in kg/day, DMI^2 is centred to mean DMI of 12.6 kg/d, EE intake (kg/d); OMDm, NDF, and NFC are as defined above.

Appendix 2

Mitigation options summary table

- **Table A1** Feed additives and feeding strategies offering non-CO_2 greenhouse gas mitigation opportunities
- **Table A2** Manure handling strategies offering non-CO_2 greenhouse gas mitigation opportunities
- **Table A3** Animal management strategies offering non-CO_2 greenhouse gas mitigation opportunities
- **Table A4** Reproductive management strategies offering non-CO_2 greenhouse gas mitigation opportunities
- **Table A5** Examples of interactions among non-CO_2 greenhouse gas mitigation practices

TABLE A1

Feed additives and feeding strategies offering non-CO_2 greenhouse gas mitigation opportunities

Category[1]	Potential CH_4 mitigating effect[2]	Long-term effect established	Effective[3]	Environmentally safe or safe to the animal[4]	Recommended[5]	Applicability to region[6]
Inhibitors						
BCM/BES[7]	High	?	Yes	No[8]	No	N/A
Chloroform	High	No?	Yes	No	No	N/A
Cyclodextrin	Low	No	Yes	No	No	N/A
Electron receptors						
FMA[9]	No effect to High	?	?	Yes	No?	N/A
Nitroethane	Low	No	Yes?	No	No	N/A
Nitrate	High	No?	Yes	?	Yes?[10]	All
Ionophores[11]	Low[12]	No?	Yes?[12]	Yes?	Yes?	NA,SA,AF,AS
Plant bioactive compounds[13]						
Tannins[14] (condensed)	Low	No?	Yes	Yes	Yes?	All
Saponins	Low?	No	?	Yes	No?	N/A
Essential oils	Low?	No	?	Yes	No	N/A
Exogenous enzymes	No effect to Low	No	No?	Yes?	No?	N/A
Defaunation	Low	No	?	Yes	No	N/A
Manipulation of rumen archaea and bacteria	Low	No	?	Yes?	Yes?[15]	NA,EU,OC
Dietary lipids	Medium	No?	Yes	Yes	Yes?[16]	All
Concentrate inclusion[17]	Low to Medium	Yes	Yes	Yes	Yes?[18]	All
improving forage quality and management	Low to Medium	Yes	Yes	Yes	Yes	All
Grazing management	Low	Yes	Yes?	Yes	Yes?[19]	All
Feed processing	Low	Yes	Yes[20]	Yes[20]	Yes[20]	All
Mixed rations and feeding frequency	? [21]	? [21]	? [21]	Yes	?[21]	All
Processing of low-quality feeds						
Reducing herd size	High	Yes	Yes	Yes	Yes	All, but mostly AF, AS, SA
Macro-supplementation (when deficient)	Medium	Yes	Yes	Yes	Yes	All, but mostly AF, AS, SA
Micro-supplementation (when deficient)	N/A	No	Yes?	Yes	Yes	
Micro-supplementation (when deficient)	N/A	No	Yes?	Yes	Yes	

(Cont.)

TABLE A1 *(Cont.)*

Feed additives and feeding strategies offering non-CO_2 greenhouse gas mitigation opportunities

Category[1]	Potential CH_4 mitigating effect[2]	Long-term effect established	Effective[3]	Environmentally safe or safe to the animal[4]	Recommended[5]	Applicability to region[6]
Alkaline treatment	Low	Yes	Yes	?	?	AF, AS, SA
Biological treatment	?	Yes	No	Yes	No	
Breeding for straw quality	Low	Yes	Yes	Yes	Yes	AF, AS, SA
Precision feeding and feed analyses	Low to Medium	Yes	Yes?	Yes	Yes[22]	All

?: indicates uncertainty due to limited research or lack of data, inconsistent/variable results, or lack/insufficient data on persistency of the effect.

N/A: not applicable.

[1] Mitigation strategies in this table are applicable to all ruminants.

[2] High = ≥ 30 percent mitigating effect; Medium = 10 to 30 percent mitigating effect; Low = ≤ 10 percent mitigating effect. Mitigating effects refer to percent change over a “standard practice”, i.e. study control that was used for comparison and are based on combination of study data and judgement by the authors of this document.

[3] Effectiveness is determined on the basis of: GHG mitigation potential, effect on feed intake (no negative effect is beneficial), and/or effect on animal productivity (no negative effect or improvement is beneficial).

[4] Based on EPA data, MSDS, or expert opinion.

[5] Based on available research or lack of sufficient research.

[6] Regions: All = all regions; EU = Europe, AS = Asia, AF = Africa, NA = North America; SA = South America; OC = Oceania.

[7] Bromochloromethane and 2-bromo-ethane sulfonate.

[8] Class I ozone-depleting substance (http://www.epa.gov/ozone/science/ods/classone.html).

[9] Fumaric and malic acids.

[10] Practicality of use is unknown. Caution must be exercised when feeding nitrate. Animal should be properly adapted and re-adapted, if nitrate supplementation is discontinued for a period of time. Access to molasses blocks with nitrate should be limited so that nitrate intake does not poison the animal. Unwise to use when diets have high N concentrations.

[11] Most data are for monensin. Monensin does not appear to have a consistent direct effect on enteric CH_4 production in dairy or beef cattle. Meta-analyses have shown improvement in feed efficiency in beef cattle (Goodrich *et al.*, 1984) and dairy cows (Duffield *et al.*, 2008) that may reduce enteric CH_4 emissions per unit of product (meat or milk). On this basis, the overall conclusion is that ionophores likely have a CH_4 mitigating effect in ruminants of up to 5 percent.

[12] Through improvement in feed efficiency, especially when diets contain concentrates; no effect when pasture is fed as a sole diet.

[13] See text for extensive discussion on these supplements. Tannins appear more effective than saponins. Results with tea samponins are encouraging but must be confirmed and data for persistence of the effect are lacking.

[14] Detrimental effects when dietary CP is marginal or inadequate or when condensed tannins are astringent and in high concentrations, but with adequate dietary CP some condensed tannins can have wide ranging benefits.

[15] Promising, but the technology is not yet developed or commercially available.

[16] Lipids are generally effective in reducing enteric CH_4 production. They are recommended, when their use is economically feasible (high-oil by-products of the biofuel industries, for example). Their potential negative effect on feed intake, fibre digestibility, rumen function, milk fat content and overall animal productivity must be considered. Maximum recommended inclusion rate in ruminant diets is 6 to 7 percent (total fat) of dietary DM. With the lack of incentive mechanisms to reduce enteric CH_4 emissions, the economic feasibility of supplementing diets with edible lipids is questionable.

[17] Higher rates of concentrate inclusion may decrease intake, but production is usually increased. Negative effects on fibre degradability and milk composition (in dairy cows) must be avoided.

[18] Although recommended (direct reduction in enteric CH_4 emission or indirect, through increased animal production), the applicability of this mitigation practice will heavily depend on feed availability. See text for further discussion.

[19] Not very consistent results, but recommended on the base that improving pasture quality should reduce CH_4 emissions per unit of feed intake and animal product.

[20] Conditionally effective (if fibre degradability is not decreased), safe to the environment (energy input may counteract GHG mitigating effect; has to be determined using LCA), and recommended (if economically feasible and does not jeopardize fibre digestibility).

[21] Insufficient data.

[22] Even if direct CH_4 mitigation effect is uncertain, precision/balanced feeding and accurate feed analyses will likely enhance animal productivity and feed efficiency and improve farm profitability (thus have an indirect mitigating effect on enteric and manure CH_4 and N_2O emissions).

TABLE A2

Manure handling strategies offering non-CO_2 greenhouse gas mitigation opportunities

Category	Species[1]	Potential CH_4 mitigating effect[2]	Potential N_2O mitigating effect[2]	Potential NH_3 mitigating effect[2]	Effective[3]	Recommended[4]	Applicability to region[5]
Dietary manipulation and nutrient balance							
Reduced dietary protein	AS	?[6]	Medium	High	Yes (N_2O, NH_3)	Yes (N_2O, NH_3)	All
High fibre diets	SW	Low	High	?	Yes (N_2O)	Yes (N_2O)	All
Grazing management							
Grazing intensity[7]	AR	?	High?[7]	?[7]	Yes (N_2O)	Yes (N_2O)	All
Housing							
Biofiltration	AS	Low?	?	High	Yes (NH_3, CH_4?)	Yes (NH_3, CH_4?)	All
Manure system[8]	DC, BC, SW	High	?	High	Yes (CH_4, NH_3)	Yes (CH_4, NH_3)	All
Manure treatment							
Anaerobic digestion	DC, BC, SW	High	High[9]	Increase?[10]	Yes (CH_4, N_2O)	Yes (CH_4, N_2O)	All
Solids separation	DC, BC	High	Low?[9]	?[11]	Yes (CH_4)	Yes (CH_4)	NA,SA,EU, OC
Aeration	DC, BC	High	Increase?[12]	?[12]	Yes (CH_4)	Yes (CH_4)	NA,SA,EU
Manure acidification	DC, BC, SW	High	?[13]	High[13]	Yes (CH_4, NH_3)	Yes (CH_4, NH_3)	NA,EU,OC
Manure storage							
Decreased storage time	DC, BC, SW	High[14]	High[14]	High[14]	Yes (all)	Yes (all)	All
Storage cover with straw	DC, BC, SW	High	Increase?[15]	High	Yes (CH_4, NH_3)	Yes (CH_4)	NA,EU
Natural or induced crust	DC, BC	High	Increase?[15]	High	Yes (CH_4, NH_3)	Yes (CH_4)	NA,EU
Aeration during liquid manure storage	DC, BC, SW	Medium to High	Increase?[12]	?[12]	Yes (CH_4)	Yes (CH_4)	NA,EU
Composting	DC, BC, SW	High	?[12]	Increase[12]	Yes (CH_4)	Yes (CH_4)	All
Litter stacking	PO	Medium	N/A	?	Yes (CH_4)	Yes (CH_4)	All
Storage temperature	DC, BC	High	?	High	Yes (CH_4, NH_3)	Yes (CH_4, NH_3)	N/A[16]
Manure application							
Manure injection vs surface application	DC, BC, SW	No effect to increase?	No effect to increase[18]	High	Yes (NH_3)	Yes (NH_3)	NA,EU,OC
Timing of application	AS	Low	High[19]	High	Yes (N_2O, NH_3)	Yes (N_2O, NH_3)	All
Soil cover, cover cropping	AS	?	No effect to High[20]	Increase?[21]	Yes (N_2O?)	Yes (N_2O?)	All
Soil nutrient balance	AS	N/A	High	High	Yes (N_2O, NH_3)	Yes (N_2O, NH_3)	All
Nitrification inhibitor[22]							
Applied to manure or after urine deposition in pastures	DC, BC, SH	N/A	High	N/A	Yes (N_2O)	Yes (N_2O)?	All[23]

(Cont.)

TABLE A2

Manure handling strategies offering non-CO_2 greenhouse gas mitigation opportunities *(Cont.)*

Category	Species[1]	Potential CH_4 mitigating effect[2]	Potential N_2O mitigating effect[2]	Potential NH_3 mitigating effect[2]	Effective[3]	Recommended[4]	Applicability to region[5]
Urease inhibitor[24]							
Applied with or before urine	DC,BC, SH	N/A	Medium?	High	Yes (N_2O, NH_3)[24]	Yes (N_2O, NH_3)?	NA,EU,OC
Soil management							
Soil condition, texture, water filled pore space, drainage	AR	?	Decrease or Increase[25]	?	Yes (N_2O)?	Yes (N_2O)?	All

?: indicates uncertainty due to limited research or lack of data, inconsistent/variable results, or lack/insufficient data on persistency of the effect.

N/A: not applicable.

[1] DC = dairy cattle; BC = beef cattle (cattle include Bos taurus and Bos indicus); SH = sheep; GO = goats; AR = all ruminants; SW = swine; PO = poultry; AS = all species.

[2] High = ≥ 30 percent mitigating effect; Medium = 10 to 30 percent mitigating effect; Low = ≤ 10 percent mitigating effect. Mitigating effects refer to percent change over a "standard practice", i.e. study control that was used for comparison and are based on combination of study data and judgement by the authors of this document.

[3] Effectiveness is determined on the basis of: GHG or NH_3 mitigation potential (in some cases, effects on feed intake and/or animal productivity were also considered).

[4] Based on available research or lack of sufficient research.

[5] Regions: All = all regions; EU = Europe, AS = Asia, AF = Africa, NA = North America; SA = South America; OC = Oceania.

[6] Insufficient research. Modelling suggests that enteric CH_4 may increase. If rumen function is impaired, manure CH_4 emissions may increase.

[7] Reduced grazing intensity can reduce up to 50 percent N_2O emissions by lowering urinary N input to the soil, but can also increase N_2O emissions by increasing residual OM during soil freeze thaw cycles. Ammonia emissions may increase, magnitude is unclear. Effectiveness varies with region. Grazing management can be practised in Western countries, Oceania, Europe and parts of central and South America and Asia, but not in some parts of the latter continents and Africa due to various constraints.

[8] Generally, a manure system that reduces the time between faeces and urine excretion and removing manure from the animal house will reduce NH_3 and CH_4 emissions from the building (data on N_2O are not conclusive and there is little N_2O emission from buildings and manure storage). For example, storing manure in the building greatly increases NH_3 and CH_4 emissions from the animal house. Type of manure system also has an effect of GHG emissions. For example, daily flushing of manure from a dairy barn will reduce NH_3 and CH_4 emissions compared with scraping. This mitigation practice reduces emissions from the building only; depending on type of storage, emissions can be greater from manure that is removed daily vs manure that resides in the animal building for longer periods of time.

[9] Anaerobic digestion and solids separation reduce the source of degradable C in the manure applied to the soil and as a consequence reduce the potential for nitrification and N_2O emissions.

[10] Ammonia emissions will increase as more organic N is decomposed to NH_3-N; magnitude is unclear.

[11] Reducing the solids content of manure facilitates infiltration and prevents NH_3 losses from land application.

[12] (see also Aeration during liquid manure storage and Composting) In some cases, aeration of manure may stimulate the transformation of NH_3-N into NO_3-N which increases the potential for N_2O emissions and reduces the potential for NH_3 volatilization. In most cases, composting increases NH_3 losses.

[13] Manure acidification decreases the fraction of volatile NH_3-N in manure, but may increase N_2O emissions after land application.

[14] Increasing the time manure is stored increases potential emissions by increasing the concentration of NH_3 and CH_4 through degradation of nutrients in manure and the time manure emissions occur, creating a compound effect varying widely in magnitude. This strategy is listed with High mitigation potential because not storing manure would be a total avoidance of storage GHG.

[15] Covering the manure with permeable porous covers promotes nitrification and N_2O emissions.

[16] Although effective, impractical to control.

[17] Covering the manure storage with impermeable covers prevents NH_3 volatilization during storage and increases the content of NH_3 in the manure, which generally results in greater of NH_3 emissions after land application.

(Cont.)

(Cont.)

[18] Injecting manure increases the soil organic C and N pools, inducing reduction conditions and promoting N_2O emissions; the magnitude of increase depends on soil moisture, texture, temperature and many other factors.

[19] Timing land application of manure to temperature and soil moisture conditions that are not conductive to nitrification and N_2O emissions can have a large but variable impact on emissions.

[20] Cover crops can increase plant N uptake and decrease accumulation of nitrate, and thus reduce N_2O production through denitrification, but the results on overall GHG emissions have not been consistent. Interactions with other soil conservation practices are significant (tillage system, for example) and must be considered when the goal of cover cropping is reducing whole-farm GHG emissions.

[21] Soil vegetation cover intercepts land applied manure, reducing infiltration and contact with soil, which results in greater NH_3 volatilization losses whose magnitude depends on the application method and manure characteristics.

[22] Nitrification inhibitors have reduced N_2O emissions and N leaching in intensive dairy and sheep production systems of Australia and New Zealand.

[23] Cost will limit applicability in developing countries.

[24] Urease inhibitors work well before urea-N in the urine is transformed to NH_3-N in manure; therefore the opportunity for application may be limited to intensive feedlot production or waste handling systems, in which faeces and urine are separated.

[25] Soil moisture content affects the nitrification and denitrification potential, resulting in large variation in N_2O emissions.

TABLE A3

Animal management strategies offering non-CO_2 greenhouse gas mitigation opportunities

Category	Species[1]	Effect on productivity	Potential CH^4 mitigating effect[2]	Potential N^2O mitigating effect[2]	Effective[3]	Recommended[4]	Applicability to region[5]
Increased productivity	AS	Increase	High[6]	High[6]	Yes	Yes	All
Recombinant bovine somatotropin	DC	Increase	Low	?	Yes?	Yes?[8]	NA,SA,AS,AF
Genetic selection (Residual Feed Intake)[7]	BC,DC,SW?	None	Low?	?	Yes	Yes?[9]	NA,EU,SA,OC
Animal health	AS	Increase	Low?	Low?	Yes	Yes	All
Reduced animal mortality	AS	Increase	Low?	Low?	Yes	Yes	All
Reduced age at harvest and reduced days on feed	AS[10]	None	Medium	Medium	Yes	Yes	All

?: indicates uncertainty due to limited research, variable results, or lack/insufficient data on persistency of the effect.

[1] DC = dairy cattle; BC = beef cattle (cattle include *Bos taurus* and *Bos indicus*); SW = swine; AS = all species.

[2] High = ≥ 30 percent mitigating effect; Medium = 10 to 30 percent mitigating effect; Low = ≤ 10 percent mitigating effect. Mitigating effects refer to percent change over a “standard practice”, i.e. study control that was used for comparison and are based on combination of study data and judgement by the authors of this document.

[3] Determined on the basis of: GHG mitigation potential and/or effect on productivity (no negative effect or improvement is beneficial).

[4] Based on available research or lack of sufficient research.

[5] Regions: All = all regions; EU = Europe, AS = Asia, AF = Africa, NA = North America; SA = South America; OC = Oceania.

[6] Increased productivity will have a powerful mitigating effect on GHG emissions, but the size of the effect will depend on a variety of factors (baseline productivity, type of animal, type of production, feed quality and availability, genetic makeup of the herd, etc.).

[7] RFI x nutrition interaction apparent with CH_4 reductions occurring in high quality diets or pastures.

[8] Depends on national regulations.

[9] Uncertain results and requires significant investment; probably impractical for many developing countries.

[10] Meat animals only.

TABLE A4

Reproductive management strategies offering non-CO_2 greenhouse gas mitigation opportunities[1]

Category	Species[1]	Relative Effectiveness[2]	Input required to achieve desired effect[3]	Applicability to region[4]
Mating strategies				
Crossbreeding	AR, SW	High	Low	All
Reduced inbreeding[5]	AR, SW	Medium	Moderate	All
Genomic selection for fertility	AR, SW	Medium	High	Developed
Improved productive life				All
Early puberty	AR, SW	Medium	Moderate	All
Early weaning	AR, SW	Medium	Moderate/ High	All
Reduce seasonality	AR, SW	Medium	Moderate	All
Enhanced fecundity[6]				
Increased litter size	SW, SH, GO	High	High	China
Increased litter/yr	SW, SH, GO	High	High	China
Prolific breeds	SW, SH, GO	High	Low	All
Gene introgression	SW, SH, GO	High	High	All
Extended breeding season	SH, GO	Medium	Moderate/ Low	Developed
Periparturient care/health				
Shorten dry period	DC	Medium	Low	Developed
Increase dry matter Intake	DC	Medium	Moderate	Developed
Dietary lipids	AR	Medium	High	Developed
Vaccination	AR, SW	Medium	Moderate	All
Reduction of stressors				
Heat	AR, SW	High	Low/ Moderate	All
Handling/transport	AR, SW	Medium?	Moderate/ Low	
Disease	AR, SW	High	Moderate/ High	All
Nutrition	AR, SW	High	Moderate	All?

(Cont.)

TABLE A4 *(Cont.)*

Reproductive management strategies offering non-CO_2 greenhouse gas mitigation opportunities[1]

Category	**Species**[1]	**Relative Effectiveness**[2]	**Input required to achieve desired effect**[3]	**Applicability to region**[4]
Assisted reproductive technologies[7]				
Artificial insemination	AR, SW	High	Moderate/ High	All?
Hormonal synchronization	AR, SW	Medium	High	Developed
Embryo transfer	AR, SW	High	High	Developed
Gender-selected				
Pregnancy diagnosis	AR	High	High	All

[1] All mitigation strategies in this table are recommended if they are supported by other aspects of the production system (e.g. nutrition, facilities, etc.). DC = dairy cattle; BC = beef cattle (cattle include *Bos taurus* and *Bos indicus*); SH = sheep;
GO = goats; AR = all ruminants; SW = swine.

[2] Determined on the basis of magnitude of expected effect on fertility: High (Highly Effective), > 5 percent increase in pregnancy rate (number of animals conceiving during the breeding season) or fecundity (number of offspring born during a breeding season); Medium (Medium Effective), 1 to 5 percent. Based on combination of study data and judgement by the authors of this document.

[3] High = substantial facilities, resources or training needed; Moderate = some facility improvements, enhanced resources or training needed; Low = few/modest facility improvements, enhanced resources or training needed.

[4] Regions: All = all regions; Developed = developed countries.

[5] Estimates represent estimates of inbreeding of 20 percent in purebred sheep (Ercanbrack and Knight, 1991) and of 5 to 15 percent in dairy cattle (Soares *et al.*, 2011; Panetto *et al.*, 2010). Each 1 percent increase in inbreeding in sheep results in a 1 percent decline in lambs weaned per ewe. Average inbreeding coefficients in purebred sheep breeds was 20-30 percent (Ercanbrack and Knight, 1991).

[6] China: potential decrease in animal numbers: 320 000 to 2 250 000; potential CH_4 and N_2O mitigating effect, 2.5 to 7.5 percent. Estimates represent reduction in sow numbers possible in breeding herd in China if litter size increased by 1 pig/litter (to United States level of 10.3 pigs weaned/litter) and 0.4 increase in litters per year (to United States level of 2.3). Results reflect potential mitigation in the commercial swine industry which represents about 40 percent of production (remaining 60 percent are smallholder/backyard operations). If applied to the remainder of production, the effect would be significantly greater (*Profile of China Pig Industry and Development,* President, China National Swine Industry Association).

[7] Potential decrease in animal numbers: > 5 percent; potential CH_4 and N_2O mitigating effect, 3.5 to 5.5 percent. Estimates represents 14 million fewer replacement dairy animals needed with a 5 percent increase in dairy conception rate. This will also increase lifetime milk production and, potentially, productive life.

TABLE A5

Examples of interactions among non-CO_2 greenhouse gas mitigation practices[1]

Mitigation practice	Potential interactions	Production system to which interaction may be applicable
Enteric CH_4 mitigation practices		
Electron receptors (nitrates)	Potential for increased N_2O emission from soil from urinary and manure deposition, including manure applied to soil.	RC, RM, RG[2]
Balanced dietary protein	Will decrease manure NH_3 and N_2O emissions, but may (based on limited modelling data) increase enteric CH_4 production due to increased proportion of dietary carbohydrates replacing decreased protein. Decreasing dietary protein should be implemented in a manner to avoid any decrease in feed intake and animal production, or Ei will increase.	RC, RM, RG, MI, MM, MB
Dietary lipids	Can reduce digestibility, feed intake, and animal productivity, thus increasing Ei. Can increase CH_4 from stored manure, if source is from oilseeds (e.g. cottonseed). Not recommended with low-quality diets (< 50 percent digestibility). Do not exceed 6 percent ether extract (total fat) in higher-quality diets.	RC, RM
Concentrate inclusion	Can decrease enteric CH_4 if > 35 to 40 percent (starchy concentrates). Expect productivity effects, and decreased Ei, at lower inclusion levels. Fibre digestibility can decrease at high inclusion (> 40 percent starchy concentrates). Can lead to higher volatile solids excretion in manure, and thus higher CH_4 emission during manure storage. Highly digestible diets will, however, produce less manure and manure C.	RC, RM
Grazing management	Optimize productivity per unit of land by maximizing digestible dry matter intake. Increase fodder quality to a level that does not exceed balanced protein requirements, or N_2O emissions may increase.	RM, RG
Feed processing (grains)	Could have positive effect on enteric CH_4, CH_4 from stored manure and N_2O emissions from manure application, if rumen function is not negatively affected.	RC, RM
Alkaline treatment of low-quality feeds	If anhydrous NH_3 or urea is used, can lead to increased NH_3 emissions.	RC, RM
Strategic supplementation of low-quality feeds	Increased feed intake, but may lead to increased manure N excretion and potentially NH_3 and N_2O emissions. Increased absolute enteric CH_4, but decreased Ei.	RM, RG
Precision feeding	Will reduce N and volatile solids content in manure, thus NH_3 , N_2O and CH_4 emissions	RC
Manure mitigation practices		
Dietary tannins	Main effect is to reduce NH_3 emissions. Can reduce N_2O emissions from manure application to soil: directly, through binding to proteins and indirectly, through diverting N from urine to faeces. Can reduce CH_4 emission from stored manure. Can lead to lower intake and decreased digestibility in high-tannin forages.	RC, RM, RG
Tannins added to manure	Slow down decomposition of manure and, consequently, decreases CH_4 emissions from stored manure. Should not be used with anaerobic digestion.	RC, MI, MM

(Cont.)

TABLE A5 *(Cont.)*

Examples of interactions among non-CO_2 greenhouse gas mitigation practices[1]

Mitigation practice	Potential interactions	Production system to which interaction may be applicable
Anaerobic digestion	Can increase NH_3 emission during manure storage and application of manure liquor.	RC, MI, MM, MB
Grazing management (intensity, stand-off pads)	Grazing intensity – same effects as for enteric CH_4. Stand-off pads: main effect on reducing N_2O emission from urine patches, but can also increase CH_4 in manure deposited in anaerobic conditions. May reduce fertilizer use.	RM, RG
Decreased manure storage time	Directly reduces all gaseous emissions from manure storage. Possible increase in N_2O emissions when manure is applied to soil. Shorter storage time means more frequent soil application: may have both positive and negative effects on GHG emissions from soil, depending on season.	RC, RM, MI, MM, MB
Natural or induced manure crust	Direct reduction of CH_4 emission. Also reduces NH_3 emissions, but may increase N_2O emissions.	RC, RM, MI, MM
Composting	Reduces CH_4 and perhaps N_2O emissions, but increases NH_3 emissions and total manure N losses. Overall GHG emission reduction effect.	
Acidification and decreasing manure temperature (storing outside in cold climate zones)	Will generally reduce NH_3 and CH_4 emissions; interaction effects weak or not well understood.	RC, RM, MI, MM
Sealed storage with flare	Effectively mitigates CH_4 emissions, but may increase NH_3 emission during storage and soil application of manure liquor.	RC, MI, MM, MB
Subsurface manure incorporation	Main effect is to decrease N_2O emissions; it may also decrease NH_3 losses, thus reducing the need for N fertilizer. May create localized anaerobic conditions and thus result in increased CH_4 emissions.	RC, RM, MI, MM, MB
Soil cover, cover cropping	Main effect is to enhance uptake of nitrates by plants resulting in lower N_2O emissions, but results have been inconsistent; could lead to higher overall N_2O loss in high rainfall systems and there are significant interactions with other soil conservation practices (no-tillage, for example).	RC, RM, MI, MM, MB
Nitrification inhibitors	Can increase NH_3 emissions, depending on manure storage. Can increase forage and pasture production (or displace N fertilizer).	RC, RM, RG, MI, MM, MB
Urease inhibitors	Reduce NH_3 losses, but can increase N_2O emissions.	RC, MI

[1] This table is constructed on the basis of discussions about mitigation practices among FAO experts and the authors of this document.

[2] Animal production system: RC = ruminants, confined; RM = ruminants, mixed; RG = ruminants, grazing; MI = monogastrics, industrial (large scale, all concentrate feed, commercial); MM = monogastrics, intermediate (medium scale, feeding is with concentrate and by-products, commercial); MB = backyard (mostly fed on swill and browsing, not commercial).

Bibliography

Aarnik, A.J.A., van den Berg, A.J., Keen, A., Hocksma, P. & Verstegen, M.W.A. 1996. Effect of slatted floor area on ammonia emission and on the excretory and lying behaviour of growing pigs. *J. Agric. Eng. Res.* 64: 299–310.

Abecia, L., Martin-Garcia, A. I., Martinez, G., Tomkins, N.W., Newbold, C.J. & Yaňez-Ruiz, D.R. 2011. Manipulation of the rumen microbial ecosystem to reduce methane emissions in ruminants through the intervention at early life stage of pre-ruminants and their mothers. *Adv. Anim. Biosci.* 2: 271.

Abecia, L., Toral, P.G., Martín-García, A.I., Martínez, G., Tomkins, N.W., Molina-Alcaide, E., Newbold, C.J. & Yaňez-Ruiz, D.R. 2012. Effect of bromochloromethane on methane emission, rumen fermentation pattern, milk yield, and fatty acid profile in lactating dairy goats. *J. Dairy Sci.* 95: 2027–2036.

Abbeddou, S., & Makkar, H.P.S. 2012. Potential and constraints in utilizing co-products of the non-edible oils-based biodiesel industry – an overview. *In* H.P.S. Makkar, ED. *Biofuel co-products as livestock feed – Opportunities and challenges*, pp. 327-340. Rome, FAO.

Abegaz, A., van Keulen, H. & Oosting, S.J. 2007. Feed resources, livestock production and soil carbon dynamics in Teghane, Northern Highlands of Ethiopia. *Agric. Syst.* 94: 391–404.

Abou Nohra, J., Barrington, S., Frigon, J.C. & Guiot, S.R. 2003. In storage psychrophilic anaerobic digestion of swine slurry. *Resour. Conserv. Recycl.* 38: 23–37.

Abrahamse, P.A., Tamminga, S. & Dijkstra. J. 2009. Effect of daily movement of dairy cattle to fresh grass in morning or afternoon on intake, grazing behaviour, rumen fermentation and milk production. *J. Agric. Sci., Camb.* 147: 721–730.

Adom, F., Maes, A., Workman, C., Clayton-Nierderman, Z., Thoma, G. & Shonnard, D. 2012. Regional carbon footprint analysis of dairy feeds for milk production in the USA. *Int. J. Life Cycle Assess.* 17: 520–534.

Agle, M., Hristov, A.N., Zaman, S., Schneider, C., Ndegwa, P. & Vaddella, V.K. 2010a. Effects of ruminally degraded protein on rumen fermentation and ammonia losses from manure in dairy cows. *J. Dairy Sci.* 93: 1625-1637.

Agle, M., Hristov, A.N., Zaman, S., Schneider, C., Ndegwa, P. & Vaddella, V.K. 2010b. Effect of dietary concentrate on rumen fermentation, digestibility, and nitrogen losses in dairy cows. *J. Dairy Sci.* 93: 4211–4222.

Aguerre, M.J., Wattiaux, M.A. M. Capozzolo, C., Lencioni, P. & Cabral, C. 2010. Effect of quebracho-chestnut tannin extracts at two dietary crude protein levels on nitrogen partitioning in lactating dairy cows. *J. Dairy Sci.* 93(E-Suppl. 1): 446 (Abstr.).

Aguerre, M.J., Wattiaux, M.A., Powell, J.M., Broderick, G.A. & Arndt, C. 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. *J. Dairy Sci.* 94: 3081–3093.

Ahn, J.H. & Forster, C.F. 2002. A comparison of mesophilic and thermophilic anaerobic upflow filters treating paper-pulp-liquors. *Process Biochem.* 38: 257–262.

Aikman, P.C., Henning, P.H., Humphries, D.J. & Horn, C.H. 2011. Rumen pH and fermentation characteristics in dairy cows supplemented with *Megasphaera elsdenii* NCIMB 41125 in early lactation. *J. Dairy Sci.* 94: 2840–2849.

Alaboudi, R. & Jones, G.A. 1985. Effects of acclimation to high nitrate intake on some rumen fermentation parameters in sheep. *Can. J. Anim. Sci.* 65: 841–849.

Albrecht, K.A. &Muck, R.E. 1991. Proteolysis in ensiled forage legumes that vary in tannin concentration. *Crop Sci.* 31: 464–469.

Alemu, A.W., Dijkstra, J., Bannink, A., France, J. & Kebreab, E. 2011. Rumen stoichiometric models and their contribution and challenges in predicting enteric methane production. *Anim. Feed Sci. Technol.* 166–167: 761–778.

Allen, M.S. 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. *J. Dairy Sci.* 83: 1598–1642.

Allen, N.S., Edge, M. Sandoval, G., Verran, J., Stratton, J. & Maltby, J. 2005. Photocatalytic coatings for environmental applications. *Photochem Photobiol.* 81: 279–290.

Allen, M.S., Bradford, B.J. & Oba, M. 2009. Board invited review: The hepatic oxidation theory of the control of feed intake and its application to ruminants. *J. Anim. Sci.* 87: 3317–3334.

Allison M.J. & Reddy, C.A. 1984. Adaptations of gastrointestinal bacteria in response to changes in dietary oxalate and nitrate. *In* Klug M.J & Reddy, C.A., eds. *Current Perspectives in Microbial Ecology,* Proceedings of the 3rd International Symposium on Microbial Ecology, pp. 248–256. Washington D.C., American Society for Microbiology.

Amann, R.P. & DeJarnette, J.M. 2012. Impact of genomic selection of AI dairy sires on their likely utilization and methods to estimate fertility: A paradigm shift. *Theriogen*. 77: 795–817.

Ambus, P., Petersen, S.O. & Soussana, J.F. 2007. Short-term carbon and nitrogen cycling in urine patches assessed by combined carbon-13 and nitrogen-15 labelling. *Agric. Ecosyst. Environ.* 121: 84–92.

Amon, B., Amon, T. Boxberger, J. & Alt, C. 2001. Emissions of NH_3, N_2O and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). *Nutr. Cycl. Agroecosyst.* 60: 103–113.

Amon, B., Kryvoruchko, V., Amon T. & Zechmeister-Boltenstern, S. 2006. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agric. Ecosyst. Environ.* 112: 153–162.

Andres, S., Giraldez, F.J., Gonzalez, J.S., Pelaez, R., Prieto, N.& Calleja, A. 2005. Prediction of aspects of neutral detergent fibre digestion of forages by chemical composition and near infrared reflectance spectroscopy. *Aust. J. Agric. Res.* 56: 187–193.

Annen, E.L., Collier, R.J., McGuire, M.A, Vicini, J.L., Ballam, J.M. & Lormore, M.J. 2004. Effect of modified dry period lengths and bovine somatotropin on yield and composition of milk from dairy cows. *J. Dairy Sci.* 87: 3746–3761.

Appuhamy, J. A. D. R. N, A. B. Strathe, S. Jayasundara, C. Wagner-Riddle, J. Dijkstra, J. France, and E. Kebreab. 2013. Anti-methanogenic effects of monensin in dairy and beef cattle: a meta-analysis. *J. Dairy Sci.* (in press).

Araji, A.A., Abdo, Z.O. & Joyce, P. 2001. Efficient use of animal manure on cropland – economic analysis. *Biores. Technol.* 79:179–191.

Archimède, H., Eugène, M., Magdeleine, C.M., Boval, M., Martin, C., Morgavi, D.P., Lecomte, P. & Doreau, M. 2011. Comparison of methane production between C3 and C4 grasses and legumes. *Anim. Feed Sci. Technol.* 166–167: 59–64.

Arieli, A. 1992. Energetic value of whole cottonseeds fed for maintenance of sheep at 2 levels in the diet. *Livest. Prod. Sci.* 31: 301–311.

Arriaga, H., Salcedo, G., Calsamiglia, S. & Merino, P. 2010. Effect of diet manipulation in dairy cow N balance and nitrogen oxides emissions from grasslands in northern Spain. *Agric. Ecosyst. Environ.* 135: 132–139.

Arriola, K.G., Kim, S.C., Staples, C.R. & Adesogan, A.T. 2011. Effect of fibrolytic enzyme application to low- and high-concentrate diets on the performance of lactating dairy cattle. *J. Dairy Sci.* 94: 832–841.

Asanuma, N., Iwamoto, M. & Hino, T. 1999. Effect of the addition of fumarate on methane production by ruminal microorganisms *in vitro*. *J. Dairy Sci.* 82: 780–787.

Aschemann, M., Lebzien, P., Hüther, L., Döll, S., Südekum, K.H. & Dänicke, S. 2012. Effect of niacin supplementation on digestibility, nitrogen utilisation and milk and blood variables in lactating dairy cows fed a diet with a negative rumen nitrogen balance. *Arch. Anim. Nutr.* 66: 200–214.

Atakora, J.K.A., Moehn, S. & Ball, R.O. 2011a. Enteric methane produced by finisher pigs is affected by dietary crude protein content of barley grain based, but not by corn based, diets. *Anim. Feed Sci. Technol.* 166–167: 412–421.

Atakora, J.K.A., Moehn, S., Sands, J.S. & Ball, R.O. 2011b. Effects of dietary crude protein and phytase-xylanase supplementation of wheat grain based diets on energy metabolism and enteric methane in growing finishing pigs. *Anim. Feed Sci. Technol.* 166–167: 422–429.

Atasoglu, C., Newbold, C.J. & Wallace, R.J. 2001. Incorporation of [(15)N] ammonia by the cellulolytic ruminal bacteria *Fibrobacter succinogenes* BL2, *Ruminococcus albus* SY3, and *Ruminococcus flavefaciens* 17. *Appl. Environ. Microbiol.* 67: 2819–2822.

Atwell, O.G., Jaster, E.H., Moore, K.J. & Fernando, R.L. 1988. Evaluation of high oil corn and corn silage for lactating cows. *J. Dairy Sci.* 71: 2689–2698.

Auldist, M.J., O'Brien, G., Cole, D., Macmillan, K.L. & Grainger, C. 2007. Effects of varying lactation length on milk production capacity of cows in pasture-based dairying systems. *J. Dairy Sci.* 90: 3234–3241.

Baijukya, F.P., de Ridder, N. Masuki, K.F. & Giller, K.E. 2005. Dynamics of banana-based farming systems in Bukoba District, Tanzania: changes in land use, cropping and cattle keeping. *Agric. Ecosyst. Environ.* 106: 395–406.

Baker, D.H., Katz, R.S. & Easter, R.A. 1975. Lysine requirement of growing pigs at two levels of dietary protein. *J. Anim. Sci.* 40: 851–856.

Ball, R.O. & S. Mohn. 2003. Feeding strategies to reduce greenhouse gas emissions from pigs. Advances in Pork Production, Proc. 2003 Banff Pork Seminar, Alberta, Canada.14: 301-311.

Banda, J.L., Kamwanja, L.A., Chagunda, M.G., Ashworth, G.C.J. & Roberts, D.J. 2011. Status of dairy cow management and fertility in smallholder farms in Malawi. *Trop. Anim. Health Prod.* 44: 715–727.

Bannink, A., France, J., Lopez, S., Gerrits, W.J.J., Kebreab, E., Tamminga, S. & Dijkstra, J. 2008. Modelling the implications of feeding strategy on rumen fermentation and functioning of the rumen wall. *Anim. Feed Sci. Technol.* 143: 3–26.

Bannink, A., Van Schijndel, M.W. & Dijkstra, J. 2011. A model of enteric fermentation in dairy cows to estimate methane emission for the Dutch National Inventory Report using the IPCC Tier 3 approach. *Anim. Feed Sci. Technol.* 166–167: 603–618.

Bargo, F., Muller, L.D., Delahoy, J.E. and Cassidy, T.W. 2002. Performance of high producing dairy cows with three different feeding systems combining pasture and total mixed rations. *J. Dairy Sci.* 85: 2948–2963.

Basarab, J.A., Baron, V.S. & Okine, E.K. 2009. Discovering nutrition related opportunities in the carbon credit system for beef cattle. *In* Proceedings of the 30th Western Nutrition Conference, September 23–24, 2009, Winnipeg, Manitoba, Canada.

Basset-Mens, C., Ledgard, S. & Boyes, M. 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. *Ecol. Econ.* 68: 1615–1625.

Baudracco, J., Lopez-Villalobos, N., Holmes, C.W. & Macdonald, K.A. 2010. Effects of stocking rate, supplementation, genotype and their interactions on grazing dairy systems: a review. *N. Z. J. Agric. Res.* 53: 109–133.

Bavin, T.K., Griffis, T.J., Baker, J.M. & Venterea, R.T. 2009. Impact of reduced tillage and cover cropping on the greenhouse gas budget of a maize/soybean rotation ecosystem. *Agric. Ecosyst. Environ.* 134:234–242.

Bayaru, E., Kanda, S., Kamada, T., Andoh, S., Nishida, T., Ishida, M., Itoh, T., Nagara, K. & Isobe, Y. 2001. Effect of fumaric acid on methane production, rumen fermentation and digestibility of cattle fed roughage alone. *Anim. Sci. J.* 72:139–146.

Beauchemin K.A. & McGinn, S.M. 2006. Enteric methane emissions from growing beef cattle as affected by diet and level of intake. *Can. J. Anim. Sci.* 86:401–408.

Beauchemin, K.A. & Rode, L.M. 1999. Optimum processing of barley. *Southern Alberta Beef Review*. 1(3). (Available at http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/beef3987

Beauchemin, K.A., McAllister, T.A., Dong, Y., Farr, B.I. & Cheng, K.J. 1994. Effects of mastication on digestion of whole cereal grains by cattle. *J. Anim. Sci.* 72:236–246.

Beauchemin, K.A., McGinn, S.M., Martinez, T.F. & McAllister, T.A. 2007a. Use of condensed tannin extract from quebracho trees to reduce methane emissions from cattle. *J. Anim. Sci.* 85:1990–1996.

Beauchemin, K.A., McGinn, S.M. & Petit, H.V. 2007b. Methane abatement strategies for cattle: Lipid supplementation of diets. *Can. J. Anim. Sci.* 87:431–440.

Beauchemin, K.A., McAllister, T.A. & McGinn, S.M. 2009a. Dietary mitigation of enteric methane from cattle. CAB Reviews: perspectives in agriculture, veterinary science. *Nutr. Nat. Res.* 4:1–18.

Beauchemin, K.A., McGinn, S.M., Benchaar, C. & Holtshausen L. 2009b. Crushed sunflower, flax, or canola seeds in lactating dairy cow diets: Effects on methane production, rumen fermentation, and milk production. *J. Dairy Sci.* 92:2118–2127.

Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T.A. & McGinn, S.M. 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. *Agric. Syst.* 103:371–379.

Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T.A. & McGinn, S.M. 2011. Mitigation of greenhouse gas emissions from beef production in western Canada – Evaluation using farm-based life cycle assessment. *Anim. Feed Sci. Technol.* 166–167: 663–677.

Bee, J.K.A., Msanga, Y.N. & Kavana, P.Y. 2006. Lactation yield of crossbred dairy cattle under farmer management in Eastern coast of Tanzania. Livest. Res. Rural Dev. 18. (Accessed on 2 February 2006 at http://www.cipav.org.co/lrrd/lrrd18/2/bee18023.htm).

Beegle, D.B., Kelling, K.A. & Schmitt, M.A. 2008. Nitrogen from animal manure. *In* J.S. Schepers & W.R. Raun, eds. *Nitrogen in Agricultural Systems*, pp. 832–881. Madison, WI, USA, American Society of Agronomy,

Beever, D.E. 2006. The impact of controlled nutrition during the dry period on dairy cow health, fertility and performance. *Anim. Reprod. Sci.* 96: 212–226.

Bell, M.J., Wall, E., Simm, G., Russell, G. & Roberts, D.J. 2008. Reducing dairy herd methane emissions through improved health, fertility and management. *In* P. Rowlinson, M. Steele & A. Nefzaoui, eds. *Livestock and Global Climate Change*, pp. 123–126. Hammamet, Tunisia, Cambridge University Press.

Bell, M.J., Wall, E., Russell, G., Simm, G. & Stott, A.W. 2011. The effect of improving cow productivity, fertility, and longevity on the global warming potential of dairy systems*. J. Dairy Sci.* 94: 3662–3678.

Benchaar, C. & Greathead, H. 2011. Essential oils and opportunities to mitigate enteric methane emissions from ruminants. *Anim. Feed Sci. Technol.* 166–167: 338–355.

Benchaar, C., Petit, H.V., Berthiaume, R., Ouellet, D.R., Chiquette, J. & Chouinard, P.Y. 2007. Effects of essential oils on digestion, ruminal fermentation, rumen microbial populations, milk production, and milk composition in dairy cows fed alfalfa silage or corn silage*. J. Dairy Sci.* 90: 886–897.

Benchaar, C., Hristov, A.N. & Greathead, H. 2009. Essential oils as feed additives in animal nutrition. *In* T. Steiner, ed. pp. 111–146, *Phytogenics in Animal Nutrition*. Nottingham, UK Nottingham University Press.

Berglund, B. 2008. Genetic improvement of dairy cow reproductive performance. *Reprod. Dom. Anim.* 43(Suppl. 2): 89–95.

Berman, A. 2011. Invited review: Are adaptations present to support dairy cattle productivity in warm climates? *J. Dairy Sci.* 94: 2147–2158.

Bernet, N., Delgenes, N., Akunna, J.C., Delgenes, J.P. & Moletta, R. 2000. Combined anaerobic-aerobic SBR for the treatment of piggery wastewater. *Wat. Res.* 34: 611–619.

Berry, D.P., Lee, J.M., Macdonald, K.A. & Roche, J.R. 2007. Body condition score and body weight effects on dystocia and stillbirths and consequent effects on postcalving performance. *J. Dairy Sci.* 90: 4201–4211.

Bertora, C., Alluvione, F., Zavattaro, L., van Groenigen, J.W., Velthof, G. & Grignani, C. 2008. Pig slurry treatment modifies slurry composition, N_2O, and CO_2 emissions after soil incorporation. *Soil Biol. Biochem.* 40: 1999–2006.

Beukes, P.C., Gregorini, P., Romera, A.J., Levy, G. & Waghorn, G.C. 2010. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. *Agric. Ecosyst. Environ.* 136: 358–365.

Bhandral, R., Bittman, S., Kowalenko, C.G., Friesen, A. & Hunt, D.E. 2008. Emissions of nitrous oxide after application of dairy slurry on bare soil and perennial grass in a maritime climate. *Can. J. Anim. Sci.* 88: 517–527.

Bhatta, R., Enishi, O., Yabumoto, Y., Nonaka, I., Takusari, N., Higuchi, K., Tajima, K., Takenaka, A. & M. Kurihara, M. 2012. Methane reduction and energy partitioning in goats fed two concentrations of tannin from *Mimosa* spp. *J. Agric. Sci.* (Cambr.), doi:10.1017/S0021859612000299.

Bicudo, J., Schmidt, D. & Jacobson, L. 2004. Using covers to minimize odor and gas emissions from manure storages. University of Kentucky, Cooperative Extension Service, College of Agriculture (http://www.ca.uky.edu).

Bjurling, K. & Svärd, Å. 1998. Samrötning av organiskt avfall: en studie av svenska biogasanläggningar [Co-digestion of organic waste: a study of Swedish biogas plants]. Master's Thesis, Lund, Sweden: Department of Water and Environmental Engineering, Lund University (in Swedish).

Blaxter, K.L. & Clapperton, J.L. 1965. Prediction of the amount of methane produced by ruminants. *Br. J. Nutr.* 19: 511–522.

Blümmel, M., Anandan, S. & Prasad, C.S. 2009. Potential and Limitations of by-Product Based Feeding Systems to Mitigate Greenhouse Gases for Improved Livestock Productivity. *In* Proceedings of the 13th Biennial Conference of Animal Nutrition Society of India, pp. 68–74. Bangalore, India. National Institute of Animal Nutrition and Physiology.

Blümmel, M., Vishala, A., Ravi, D., Prasad, K.V.S.V., Ramakrishna Reddy, C. & Seetharama, N. 2010. Multi-environmental investigations of food-feed trait relationships in Kharif and Rabi sorghum (*Sorghum bicolor* (L) Moench) over several years of cultivars testing in India. *Anim. Nutr. Feed Technol.* 10(Suppl.1): 11–21.

Boadi, D.A. & Wittenberg, K.M. 2002. Methane production from dairy and beef heifers fed forages differing in nutrient density using the sulphur hexafluoride (SF_6) tracer gas technique. *Can. J. Anim. Sci.* 82: 201–206.

Boadi, D., Benchaar, C., Chiquette, J. & Massé, D. 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Can. J. Anim. Sci.* 84: 319–335.

Bodas, R., López, S., Fernandez, M., Garcia-González, R., Rodríguez, A.B., Wallace, R.J. & González, J.S. 2008. *In vitro* screening of the potential of numerous plant species as antimethanogenic feed additives for ruminants. *Anim. Feed Sci. Technol.* 145: 245–258.

Bol, R., Petersen, S.O., Christofides, C., Dittert, K. & Hansen, M.N. 2004. Short-term N_2O, CO_2, NH_3 fluxes, and N/C transfers in a Danish grass-clover pasture after simulated urine deposition in autumn. *J. Plant Nutr. Soil Sci.* 167: 568–576.

Bond, T. & Templeton, M.R. 2011. History and future of domestic biogas plants in the developing world. *Energ. Sust. Dev.* 15: 347–354.

Borgen, S.K., Lunde, H.W., Bakken, L.R., Bleken, M.A. & Breland, T.A. 2012. Nitrogen dynamics in stockless organic clover–grass and cereal rotations. *Nutr. Cycl. Agroecosyst.* 92: 363–378.

Börjesson, P. & Berglund, M. 2006. Environmental systems analysis of biogas systems - Part 1: Fuel-cycle emissions. *Biomass Bioenerg.* 30: 469–485.

Börjesson, P. & Berglund, M. 2007. Environmental systems analysis of biogas systems - Part II: The environmental impact of replacing various reference systems. *Biomass Bioenerg.* 31: 326–344.

Boucher, S.E., Calsamiglia, S., Parsons, C.M., Stein, H.H., Stern, M.D., Erickson, P.S., Utterback, P.L. & Schwab, C.G. 2009. Intestinal digestibility of amino acids in rumen-undegraded protein estimated using a precision-fed cecectomized rooster bioassay: II. Distillers dried grains with solubles and fish meal. *J. Dairy Sci.* 92: 6056–6067.

Boursier, H., Beline, F. & Guiziou, F. 2004. Etude et modelisation des processus biologiques au cours du traitment du lisier de porc en vue d'une optimization et d'une fiabilisation du procede. *Journees Recherche Porcine* 36: 83–90.

Braber, K. 1995. Anaerobic digestion of municipal solid waste: A modern waste disposal option on the verge of breakthrough. *Biomass Bioenerg.* 9: 365–376.

Bristow, A.W., Whitehead, D.C. & Gordon, J.E. 1992. Nitrogenous constituents in the urine of cattle sheep and goats. *J. Sci. Food. Agric.* 59: 387–394.

Brito, A.F., Tremblay, G.F., Bertrand, A., Castonguay, Y., Bélanger, G., Michaud, R., Lapierre, H., Benchaar, C., Petit, H.V., Ouellet, D.R. & Berthiaume, R. 2008. Alfalfa cut at sundown and harvested as baleage improves milk yield of late-lactation dairy cows. *J. Dairy Sci.* 91: 3968–3982.

Broderick, G.A. 1995. Desirable characteristics of forage legumes for improving protein utilization in ruminants. *J. Anim. Sci.* 73: 2760–2773.

Broderick, G.A. & Albrecht, K.A. 1997. Ruminal *in vitro* degradation of protein in tannin-free and tannin-containing forage legume species. *Crop Sci.* 37: 1884–1891.

Broderick, G.A., Koegel, R.G., Walgenbach, R.P. & Kraus, T.J. 2002. Ryegrass or alfalfa silage as the dietary forage for lactating dairy cows. *J. Dairy Sci.* 85: 1894–1901.

Broderick, G.A. & Muck, R.E. 2009. Effect of alfalfa silage storage structure and rumen-protected methionine on production in lactating dairy cows. *J. Dairy Sci.* 92: 1281–1289.

Broderick, G.A., Muck, R.E. & Grabber, J.H. 2012. Effects of replacing dietary lucerne silage with birdsfoot trefoil silage containing different levels of condensed tannin on production of lactating dairy cattle. *In* K. Kuoppala, M. Rinne & A. Vanhatalo, eds. Proceeding of the XVI International Silage Conference, pp. 150–151. MTT Agrifood Research Finland, University of Helsinki.

Brown, E.G., Anderson, R.C., Carstens, G.E.. Gutierrez-Bańuelos, H., McReynolds, J.L., Slay, L.J., Callaway, T.R. & Nisbet, D.J. 2011. Effects of oral nitroethane administration on enteric methane emissions and ruminal fermentation in cattle. *Anim. Feed Sci. Technol.* 166–167: 275–281.

Brown, J.A. & Cline, T.R. 1974. Urea excretion in the pig: an indicator of protein quality and amino acid requirements. *J. Nutr.* 104: 542-545.

Brown, S., Kruger, C. & Subler, S. 2008. Greenhouse gas balance for composting operations. *J. Environ. Qual.* 37: 1396–1410.

Buddle, B.M., Denis, M., Attwood, G.T., Altermann, E., Janssen, P.H., Ronimus, R.S., Pinares-Patiño, C.S., Muetzel, S. & Wedlock, D.N. 2011. Strategies to reduce methane emissions from farmed ruminants grazing on pasture. *Vet. J.* 188: 11–17.

Burritt, E.A., Mayland, H.F., Provenza, F.D., Miller, R.L. & Burns, J.C. 2005. Effect of added sugar on preference and intake by sheep of hay cut in the morning versus the afternoon. *Appl. Anim. Behav. Sci.* 94: 245–254.

Butler, S.T., Shalloo, L. & Murphy, J.J. 2010. Extended lactations in a seasonal-calving pastoral system of production to modulate the effects of reproductive failure. *J. Dairy Sci.* 93: 1283–1295.

Cadisch, G. & Giller, K.E. 2001 Soil organic matter management: the roles of residue quality in C sequestration and N supply. *In* R.M. Rees, B.C. Ball, C.D. Campbell & C.A. Watson, eds. *Sustainable Management of Organic Matter*, pp. 97–111. Wallingford, Oxon U.K., CAB International.

Calsamiglia, S., Busquet, M., Cardozo, P.W., Castillejos, L. & Ferret, A. 2008. Essential oils as modifiers of rumen microbial fermentation. *J. Dairy Sci.* 90: 2580–2595.

Cammack, K.M., Wright, C.L., Austin, K.J., Johnson, P.S., Cockrum, R.R., Kessler, K.L. & Olson, K.C. 2010. Effects of high-sulphur water and clinoptilolite on health and growth performance of steers fed forage-based diets. *J. Anim. Sci.* 88: 1777–1785.

Canadian Pork Council. 2006. *Demonstration project on a commercial farm of a technology that capture and oxidize methane from manure storage facilities*. Canadian Pork Council Greenhouse Gas Mitigation Program.

Canh, T.T., Verstegen, M.W.A., Aarnink, A.J.A. & Schrama, J.W. 1997. Influence of dietary factors on nitrogen partitioning and composition of urine and feces of fattening pigs. *J. Anim. Sci.* 75:700–706.

Cantalapiedra-Hijar, G., Yáñez-Ruiz, D.R., Newbold, C.J. & Molina-Alcaide, E. 2011. The effect of the feed-to-buffer ratio on bacterial diversity and ruminal fermentation in single-flow continuous-culture fermenters. *J. Dairy Sci.* 94: 1374–1384.

Cao, Y., Takahashi, T., Horiguchi, K., Yoshida, N. & Cai, Y. 2010. Methane emissions from sheep fed fermented or non-fermented total mixed ration containing whole-crop rice and rice bran. *Anim. Feed Sci. Technol.* 157: 72–78.

Cao, Y., Cai, Y., Takahashi, T., Yoshida, N., Tohno, M., Uegaki, R., Nonaka, K. & Terada, F. 2011. Effect of lactic acid bacteria inoculant and beet pulp addition on fermentation characteristics and *in vitro* ruminal digestion of vegetable residue silage. *J. Dairy Sci.* 94:3 902–3912.

Capper, J.L. & Cady, R.A. 2012. A comparison of the environmental impact of Jersey compared with Holstein milk for cheese production. *J. Dairy Sci.* 95: 165–176.

Capper, J.L., Castañeda-Gutiérrez, E., Cady, R.A. & Bauman, D.E. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. *Proc. Natl. Acad. Sci. USA* 105: 9668–9673.

Capper, J.L., Cady, R.A. & Bauman, D.E. 2009. The environmental impact of dairy production: 1944 compared with 2007. *J. Anim. Sci.* 87: 2160–2167.

Cardenas, L.M., Chadwick, D., Scholefield, D., Fychan, R., Marley, C.L., Jones, R., Bol, R., Well, R. & Vallejo, A. 2007. The effect of diet manipulation on nitrous oxide and methane emissions from manure application to incubated grassland soils. *Atmos. Environ.* 41: 7096–7107.

Carro, M.D., Ranilla, M.J., Martín-García, A.I. & Molina-Alcaide, E. 2009. Comparison of microbial fermentation of high- and low-forage diets in Rusitec, single-flow continuous-culture fermenters and sheep rumen. *Animal* 3: 527–534.

Carter, S.D., Cromwell, G.L., Lindemann, M.D. Turner, L.W. & Bridges, T.C. 1996. Reducing N and P excretion by dietary manipulation in growing and finishing pigs. *J. Anim. Sci.* 74 (Suppl. 1):59. (Abstr.)

Carulla, J.E., Kreuzer, M., Machmüller, A. & Hess, H.D. 2005. Supplementation of *Acacia mearnsii* tannins decreases methanogenesis and urinary nitrogen in forage-fed sheep. *Austr. J. Agric. Res.* 56: 961–970.

Causarano, H.J., Franzluebbers, A.J., Reeves, D.W. & Shaw, J.N. 2006. Soil organic carbon sequestration in cotton production systems of the southeastern United States: A Review. *J. Environ. Qual.* 35: 1374–1383.

Cavigelli, M.A. & Parkin, T.B. 2012. Cropland management contributions to greenhouse gas flux: Central and eastern U.S. *In* A.J. Franzluebbers & R.F. Follett, eds. *Managing Agricultural Greenhouse Gases: Coordinated Agricultural Research through GRACEnet to Address our Changing Climate*. New York, M.A. Liebig, Academic Press.

Cayuela, M.L., Oenema, O., Kuikman, P.J., Bakker, R.R. & van Groenigen, J.W. 2010. Bioenergy by-products as soil amendments? Implications for carbon sequestration and greenhouse gas emissions. *GCB Bioenergy* 2: 201–213.

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B. & Misselbrook, T. 2011. Manure management: implications for green house gas emissions. *Anim. Feed Sci. Technol.* 166–167: 514–531.

Chantigny, M.H., Angers, D.A., Rochette, P., Belanger, G., Masse, D. & Cote, D. 2007. Gaseous nitrogen emissions and forage nitrogen uptake on soils fertilized with raw and treated swine manure. *J. Environ. Qual.* 36: 1864–1872.

Chantigny, M.H., Rochette, P., Angers, D.A., Bittman, S., Buckley, K., Massé, D., Belanger, G., Eriksen-Hamel, N. & Gasser, M.O. 2010. Soil nitrous oxide emissions following band-incorporation of fertilizer nitrogen and swine manure. *J. Environ. Qual.* 39:1545–1553.

Chanvallon, A., Blache , D., Chadwick, A., Esmaili, T., Hawken, P.A., Martin, G.B., Viñoles, C. & Fabre-Nys, C. 2010. Sexual experience and temperament affect the response of Merino ewes to the ram effect during the anoestrous season. *Anim. Reprod. Sci.* 119: 205–211.

Chapman, C., Bork, E., Donkor, N. & Hudson,R. 2008. Forage yield and quality of chicory, birdsfoot trefoil, and alfalfa during the establishment year. Open Agric. J. 2: 68–74.

Charmley, E. 2001. Towards improved silage quality – A review. *Can. J. Anim. Sci.* 81: 157–168.

Chaucheyras, F., Fonty, G., Bertin, G. & Gouet, P. 1995. *In vitro* H_2 utilization by a ruminal acetogenic bacterium cultivated alone or in association with an archaea methanogen is stimulated by a probiotic strain of *Saccharomyces cerevisiae*. *Appl. Environ. Microbiol.* 61: 3466–3467.

Chianese, D.S., Rotz, C.A. & Richard, T.L. 2009. Whole-farm gas emissions: A review with application to a Pennsylvania dairy farm. *Appl. Eng. Agric*. 25: 431–442.

Chilliard, Y. & Ferlay, A. 2004. Dietary lipids and forages interactions on cow and goat milk fatty acid composition and sensory properties. *Reprod. Nutr. Dev.* 44: 467–492.

Chilliard, Y., Verite, R. & Pflimlin, A. 1989. Effets de la somatotropine bovine sur les performances des vaches laitières dans les conditions françaises d'élevage. *INRA Prod. Anim.* 2: 301–312.

Christensen, S. 1983. Nitrous-oxide emission from a soil under permanent grass - seasonal and diurnal fluctuations as influenced by manuring and fertilization. *Soil Biol. Biochem.* 15: 531–536.

Christopher, S.F. & Lal, R. 2007. Nitrogen management affects carbon sequestration in North American cropland soils. *Crit. Rev. Plant Sci.* 26: 45–64.

Christie, K., Rawnsley, R. & Donaghy, D. 2008. Whole farm systems analysis of greenhouse gas emission abatement strategies for dairy farms. UT12945. Final report to Dairy Australia on the investigation and analysis into greenhouse gas abatement strategies, modelling and decision tools for the Australian dairy industry.

Chung, Y.-H., Zhou, M., Holtshausen, L., Alexander, T.W., McAllister, T.A., Guan, L.L, Oba, M. & Beauchemin, K.A. 2012. A fibrolytic enzyme additive for lactating Holstein cow diets: Ruminal fermentation, rumen microbial populations, and enteric methane emissions. *J. Dairy Sci.* 95: 1419–1427.

Clark, H. 2010. Animal vs measurement technique variability in enteric methane production—Is the measurement resolution sufficient? *In* E.J. McGeough & S.M. McGinn, eds. Proceedings of 4th International Conference on Greenhouse Gases and Animal Agriculture, Banff, AB, Canada.

Clark, H., Wright, A.-D., Joblin, K., Molano, G., Chavanagh, A. & Peters, J. 2004. Field testing and Australian developed anti-methanogen vaccine in growing ewe lambs. *In* Proceedings of the Workshop on the Science of Atmospheric Trace gases, 18-19 March 2004, Wellington, New Zealand, pp. 107–108.

Clark, O.G., Moehn, S., Edeogu, I., Price, J. & Leonard, J. 2005. Manipulation of dietary protein and nonstarch polysaccharide to control swine manure emissions. *J. Environ. Qual.* 34: 1461–1466.

Clemens, J. & Ahlgrimm, H.J. 2001. Greenhouse gases from animal husbandry: mitigation options. *Nutr. Cycl. Agroecosyst.* 60: 287–300.

Clemens J. & Huschka, A. 2001. The effect of biological oxygen demenad of cattle slurry and soil moisture on nitrous oxide emissions. *Nutr. Cycl. Agroecosyst.* 59: 193–198.

Clemens, J., Trimborn, M., Weiland, P. & Amon, B. 2006. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agric. Ecosyst. Environ.* 112: 171–177.

Clinquart, A., Micol, D., Brundseaux, C., Dufrasne, I. & Istasse, L. 1995. Utilisation des matieres grasses chez les bovins à l'engraissement. *INRA Prod. Anim.* 8: 29–42.

Coates, D.B. 2004. Faecal NIRS–Technology for improving nutritional management of grazing cattle. Final Report of Project NAP3.121. Meat and Livestock Australia, Sydney. 47 pp. Available at http://www.mla.com.au.

Cockwill, C.L., McAllister, T.A., Olson, M.E., Milligan, D.M., Ralston, B.J., Huisma, C. & Hand, R.K. 2000. Individual intake of mineral and molasses supplements by cows, heifers and calves. *Can. J. Anim. Sci.* 80: 681–690.

Cole, N.A., Defoor, P.J., Galyean, M.L., Duff, G.C. & Gleghorn, J.F. 2006. Effects of phase-feeding of crude protein on performance, carcass characteristics, serum urea nitrogen concentrations, and manure nitrogen of finishing beef steers. *J. Anim. Sci.* 84: 3421–3432.

Colmenero, J.J. & Broderick, G.A. 2006. Effect of dietary crude protein concentration on milk production and nitrogen utilization in lactating dairy cows. *J. Dairy Sci.* 89: 1704–1712.

Colombini, S., Colombari, G., Crovetto, G.M., Galassi, G. & Rapetti, L. 2009. Tannin treated lucerne silage in dairy cow feeding. *Ital. J. Anim. Sci.* 8(Suppl. 2): 289–291.

Comfort, S. 1990. Nitrous Oxide production from injected liquid dairy manure. *Soil Sci. Soc. Am. J.* 54: 421–427

Cromwell, G.C. & Coffey, R.D. 1993. Future strategies to diminish nitrogen and phosphorus in swine manure. Pages 20–32 in Proc. NPPC Environ. Symp. "Meeting the Environmental Challenge," Minneapolis, MN.

Contreras-Govea, F.E., Muck, R.E., Mertens, D.R. & Weimer, P.J. 2011. Microbial inoculant effects on silage and *in vitro* ruminal fermentation, and microbial biomass estimation for alfalfa, bmr corn, and corn silages. *Anim. Feed Sci. Technol.* 163: 2–10.

Cook, S.R., Maiti, P.K., Chaves, A,V., Benchaar, C., Beauchemin, K.A. & McAllister, T.A. 2008. Avian (IgY) anti-methanogen antibodies for reducing ruminal methane production: *in vitro* assessment of their effects. *Aus. J. Exp. Agric.* 48: 260–264.

Coppock, C.E. 1976. Feeding methods and grouping systems. *J. Dairy Sci.* 60: 1327–1336.

Costa, A., Chiarello, G.L., Selli, E. & Guarino, M. 2012. Effects of TiO_2 based photocatalytic paint on concentrations and emissions of pollutants and on animal performance in a swine weaning unit. *J. Environ. Manage.* 96: 86–90.

Cottle, D.J., Nolan, J.V. & Wiedemann, S.G. 2011. Ruminant enteric methane mitigation: a review. *Anim. Prod. Sci.* 51: 491–514.

Crompton, L.A., Mills, J.A.N., Reynolds, C.K., France, J., Sauvant, D., van Milgen, J., Faverdin, P. & Friggens, N. 2010. Fluctuations in methane emission in response to feeding pattern in lactating dairy cows. *In* 7th International Workshop on Modelling Nutrient Digestion and Utilisation in Farm Animals, Paris, France, pp. 176–180. Wageningen, Netherlands, Wageningen Academic Publishers.

Crosson, P., Shalloo, L., O'Brien, D., Lanigan, G.J., Foley, P.A., Boland, T.M. & Kenny, D.A. 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. *Anim. Feed Sci. Technol.* 166–167: 29–45.

Crowe, M.A. 2008. Resumption of ovarian cyclicity in post-partum beef and dairy cows. *Reprod. Dom. Anim.* 43(Suppl. 5): 20–28.

Crutzen, P.J., Aselmann, I. & Seiler, W. 1986. Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. *Tellus* 388:271-284.

Cushnahan, A., Mayne, C.S. & Unsworth, E.F. 1995. Effects of ensilage of grass on performance and nutrient utilization by dairy cattle. 2. Nutrient metabolism and rumen fermentation. *Anim. Sci.* 60:347–359.

Czerkawski, J.W. & Clapperton, J.L. 1984. Fats as energy-yielding compounds in the ruminant diet. In J. Wiseman, ed. *Fats in Animal Nutrition*, pp. 249–263. Boston, MA, Butterworths.

Dann, H.M., Ballard, C.S., Grant, R.J., Cotanch, K.W., Carter, M.P. & Suekawa, M. 2006. Effects of glutamate on microbial efficiency and metabolism in continuous culture of ruminal contents and on performance of mid-lactation dairy cows. *Anim. Feed Sci. Technol.* 130: 204–224.

Davidson, E.A. 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nat. Geosci.* 2: 659–662.

Day, W., Audsley, E. & Frost, A.R. 2008. An engineering approach to modelling, decision support and control for sustainable systems. *Philos. Trans. R. Soc. Lond. Ser. B. Biol. Sci.* 363: 527–541.

de Boever, J.L., Cottyn, B.G., Vanacker, J.M. & Boucqué, C.V. 1997. Potential of solubility, enzymatic methods and NIRS to predict in situ rumen escape protein. *Neth. J. Agric. Sci.* 45: 291–306.

DEFRA (Department for Environment, Food and Rural Affairs). 2010. Ruminant Nutrition Regimes to Reduce Methane and Nitrogen Emmissions. Project AC0209 Report. DEFRA, Procurements and Contracts Division (Science R&D Team). Accessed July 11, 2012 (http://randd.defra.gov.uk/dayocument.aspx?Document=AC0209_10114_FRP.pdf; accessed on 11 July 2012).

de Gryze, S., Wolf, A., Kaffka, S.R., Mitchell, J., Rolston, D.E., Temple, S.R., Lee, J. & Six, J. 2010. Simulating greenhouse gas budgets of four California cropping systems under conventional and alternative management. *Ecol. Applic.* 20: 1805–1819.

de Gryze, S., Lee, J., Ogle, S., Paustian, K. & Six, J. 2011. Assessing the potential for greenhouse gas mitigation in intensively managed annual cropping systems at the regional scale. *Agric. Ecosyst. Environ.* 144: 150–158.

de Haas, Y., Windig, J.J., Calus, M.P.L., Dijkstra, J., De Haan, M., Bannink, A. & Veerkamp, R.F. 2011. Genetic parameters for predicted methane production and potential for reducing enteric emissions through genomic selection. *J. Dairy Sci.* 94: 6122–6134.

de Klein, C.A.M., Logtestijn, R.S.P., Meer, H.G. & Geurink, J.H. 1996. Nitrogen losses due to denitrification from cattle slurry injected into grassland soil with and without a nitrification inhibitor. *Plant Soil* 183: 161–170.

de Klein C.A.M., Eckard, R.J. & van der Weerden, T.J. 2010. Nitrous Oxide Emissions from the Nitrogen Cycle in Livestock Agriculture: Estimation and Mitigation. *In* K. Smith, *Nitrous Oxide and Climate Change*, ed. pp.107–144, University of Edinburgh, U.K., Earthscan Publications.

de Klein, C.A.M. 2001. An analysis of environmental and economic implications of nil and restricted grazing systems designed to reduce nitrate leaching from New Zealand dairy farms. II. Pasture production and cost/benefit analysis. *N.Z. J. Agric. Res.* 44:217–235.

de Klein, C.A.M., Sherlock, R.R., Cameron, K.C. & van der Weerden, T.J. 2001. Nitrous oxide emissions from agricultural soils in New Zealand—a review of current knowledge and directions for future research. *J. Royal Soc. N. Z.* 31: 543–574.

de Klein, C.A.M., Ledgard, S.F. & Clark, H. 2002. Evaluation of two potential on-farm measures for reducing greenhouse gas emissions from an average dairy farm on the West Coast of the South Island of New Zealand. *Proc. N.Z. Grassl. Assoc.* 64: 159–165.

de Klein, C.A.M., Smith, L.C. & Monaghan, R.M. 2006. Restricted autumn grazing to reduce nitrous oxide emissions from dairy pastures in Southland, New Zealand. *Agric. Ecosyst. Environ.* 112: 192–199.

de Klein, C.A.M. & Eckard, R.J. 2008. Targeted technologies for nitrous oxide abatement from animal agriculture. *Aust. J. Exp. Agric.* 48: 14–20.

de Klein, C.A.M. & Monaghan, R.M. 2011. The effect of farm and catchment management on nitrogen transformations and N_2O losses from pastoral systems — can we offset the effects of future intensification? *Curr. Opin. Environ. Sustain.* 3: 396–406.

de Klein, C.A.M., Cameron, K.C., Di, H.J., Rys, G., Monaghan, R.M. & Sherlock, R.R. 2011. Repeated annual use of the nitrification inhibitor dicyandiamide (DCD) does not alter its effectiveness in reducing N_2O emissions from cow urine. *Anim. Feed Sci. Technol.* 166–167: 480–491.

de Rensis, F. & Scaramuzzi, R.J. 2003. Heat stress and seasonal effects on reproduction in the dairy cow – a review. *Theriogen.* 60: 1139–1151.

Dechow, C.D. & Goodling, R.C. 2008. Mortality, culling by sixty days in milk, and production profiles in high- and low-survival Pennsylvania herds. *J. Dairy Sci.* 91: 4630–4639.

Dehority, B.A. & Tirabasso, P.A. 1998. Effect of ruminal cellulolytic bacterial concentrations on in situ digestion of forage cellulose. *J. Anim. Sci.* 76: 2905–2911.

DeJarnette, J.M., Leach, M.A., Nebel, R.L., Marshall, C.E., McCleary, C.R. & Moreno, J.F. 2011. Effects of sex-sorting and sperm dosage on conception rates of Holstein heifers: Is comparable fertility of sex-sorted and conventional semen plausible? *J. Dairy Sci.* 94: 3477–3483.

Dekleva, M.W., Dechow, C.D., Daubert, J.M., Liu, W.S., Varga, G.A., Bauck, S. & Woodward, B.W. 2012. Short communication: Interactions of milk, fat, and protein yield genotypes with herd feeding characteristics. *J. Dairy Sci.* 95: 1559–1564.

del Prado, A., Chadwick, D., Cardenas, L., Misselbrook, T., Scholefield, D. & Merino, P. 2010. Exploring systems responses to mitigation of GHG in UK dairy farms. *Agric. Ecosyst. Environ.* 136: 318–332.

DelGrosso, S., Parton, W., Mosier, A., Ojima, D., Kulmala, A. & Phongpan, S. 2000. General model for N_2O and N_2 gas emissions from soils due to dentrification. *Glob. Biogeochem. Cycl.* 14: 1045–1060.

Del Grosso, S.J., Wirth, T. Ogle, S.M. & Parton, W.J. 2008. Estimating agricultural nitrous oxide emissions. *EOS, Transactions, Am. Geophys. Union* 89:529-530.

Dell, C.J., Meisinger, J.J. & Beegle, D.B. 2011. Subsurface application of manures slurries for conservation tillage and pasture soils and their impact on the nitrogen balance. *J. Environ. Qual.* 40: 352–361.

DeRamus, H.A., Clement, T.C., Giampola, D.D. & Dickison, P.C. 2003. Methane emissions of beef cattle on forages: Efficiency of grazing management systems. *J. Environ. Qual.* 32: 269–277.

De Santiago-Miramontes, M.A., Luna-Orozco, J.R., Meza-Herrera, C.A., Rivas-Munoz, R., Carrillo, E., Veliz-Deras F.G. & Mellado, M. 2011. The effect of flushing and stimulus of estrogenized does on reproductive performance of anovulatory-range goats. *Trop. Anim. Health Prod.* 43:1595-1600.

Desnoyers, M., Giger-Reverdin, S., Bertin, G., Duvaux-Ponter, C. & Sauvant, D. 2009. Meta-analysis of the influence of *Saccharomyces cerevisiae* supplementation on ruminal parameters and milk production of ruminants. *J. Dairy Sci.* 92: 1620–1632.

Devant, M., Ferret, A., Calsamiglia, S., Casals, R. & Gasa, J. 2001. Effect of nitrogen source in high-concentrate, low-protein beef cattle diets on microbial fermentation studied *in vivo* and *in vitro*. *J. Anim. Sci.* 79: 1944–1953.

Devendra, C. & Leng, R.A. 2011. Feed resources for animals in Asia: Issues, strategies for use, intensification and integration for increased productivity. *Asian-Autral. J. Anim. Sci.* 24: 303–321.

DeVries, T.J. & von Keyserlingk, M.A.G. 2005. Time of feed delivery affects the feeding and lying patterns of dairy cows. *J. Dairy Sci.* 88: 625–631.

DeVries, A., Overton, M., Fetrow, J., Leslie, K., Eicker, S. & Rogers, G. 2008. Exploring the impact of sexed semen on the structure of the dairy industry. *J. Dairy Sci.* 91: 847–856.

de Vries, M. & de Boer, I.J.M. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livest. Sci.* 128:1–11.

Dewhurst, R.J. 2012. Milk production from silage: comparison of grass, legume and maize silages and their mixtures. *In* K. Kuoppala, M. Rinne & A. Vanhatalo, eds., Proc. of the XVI Int. Silage Conf. Hameenlinna, Finland, pp. 134–135. University of Helsinki, MTT Agrifood Research Finland.

Dhiman, T.R. & Satter, L.D. 1997. Yield response of dairy cows fed different proportions of alfalfa silage and corn silage. *J. Dairy Sci.* 80: 2069–2082.

Dhiman, T.R., Zaman, M.S., MacQueen, I.S. & Boman, R.L. 2002. Influence of corn processing and frequency of feeding on cow performance. *J. Dairy Sci.* 85:217–226.

Dhingra, R., Christensen, E., Liu, Y., Zhong, B., Fu, C., Yost, M. & Remains, J. 2011. Greenhouse gas emission reductions from domestic a naerobic digesters linked with sustainable sanitation in rural China. *Environ. Sci. Technol.* 45: 2345–2352.

Di, H.J. & Cameron, K.C. 2002. The use of a nitrification inhibitor, dicyandiamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland. *Soil Use Manage.* 18:395–403.

Di, H.J. & Cameron, K.C. 2003. Mitigation of nitrous oxide emissions in spray-irrigated grazed grassland by treating the soil with dicyandiamide, a nitrification inhibitor. *Soil Use Manage*. 19:284–290.

Di, H.J. & Cameron, K.C. 2005. Reducing environmental impacts of agriculture by using a fine particle suspension nitrification inhibitor to decrease nitrate leaching from grazed pastures. *Agric. Ecosyst. Environ.* 109: 202–212.

Di, H.J. & Cameron, K.C. 2012. How does the application of different nitrification inhibitors affect nitrous oxide emissions and nitrate leaching from cow urine in grazed pastures? *Soil Use Manage*. 28:54–61.

Dijkstra, J., Van Zijderveld, S.M., Apajalahti, J.A., Bannink, A., Gerrits, W.J.J., Newbold, J.R., Perdok, H.B. & Berends, H. 2011a. Relationships between methane production and milk fatty acid profiles in dairy cattle. *Anim. Feed Sci. Technol.* 166–167: 590–595.

Dijkstra, J., Oenema, O. & Bannink, A. 2011b. Dietary strategies to reducing N excretion from cattle: implications for methane emissions. *Curr. Opin. Environ. Sustainability* 3: 414–422.

Dittert, K., Bol, R., King, R., Chadwick, D. & Hatch, D. 2001. Use of a novel nitrification inhibitor to reduce nitrous oxide emission from ^{15}N-labelled dairy slurry injected into soil. *Rapid Commun. Mass Spectrom.* 15: 1291–1296.

Dohoo, I.R., DesCôteaux, L., Leslie, K., Fredeen, A., Shewfelt, W., Preston, A. & Dowling, P. 2003. A meta-analysis review of the effects of recombinant bovine somatotropin. 2. Effects on animal health, reproductive performance, and culling. *Can. J. Vet. Res.* 67: 252–264.

Dong, H., Zhu, Z., Zhou, Z., Xin, H. & Chen, Y. 2011. Greenhouse gas emissions from swine manure stored at different stack heights. *Anim. Feed Sci. Technol.* 166–167: 557–561.

Dong, Y.-H., Ouyang, Z. & Liu, S.-L. 2005. Nitrogen transformation in maize soil after application of different organic manures. *J. Environ. Sci.* (China) 17: 340–343.

Doreau, M. & Ferlay, A. 1995. Effect of dietary lipids on nitrogen metabolism in the lumen: a review. *Livest. Prod. Sci.* 43: 97–110.

Doreau, M., Martin, C., Eugène, M., Popova, M. & Morgavi, D.P. 2011a. Leviers d'action pour réduire la production de méthane entérique par les ruminants. *In* M. Doreau, R. Baumont & J.M. Perez, eds. *Gaz à effet de serre en élevage bovin : le méthane*. Dossier, *INRA Prod. Anim.* 24: 461–474.

Doreau, M., van der Werf, H.M.G., Micol, D., Dubroeucq, H., Agabriel, J., Rochette, Y. & Martin, C. 2011b. Enteric methane production and greenhouse gases balance of diets differing in concentrate in the fattening phase of a beef production system. *J. Anim. Sci.* 89:2518–2528.

Doreau, M., Rochette, Y. & Martin, C. 2012. Effect of type of forage (maize silage vs grass silage) and protein source (soybean meal vs dehydrated lucerne) in dairy cow diet on methane emission and on nitrogen losses. Proc. Symp. Emissions of Gas and Dust by Livestock, Saint-Malo, France, June 2012, 4 pp.

Dourmad, J.-Y., Rigolot, C. & van der Werf, H. 2008. Emission of greenhouse gas, developing management and animal farming systems to assist mitigation. In P. Rowlinson, M. Steele & A. Nefzaoui, eds. *Livestock and Global Climate Change*, pp. 36–39. Hammamet, Tunisia, Cambridge University Press.

Duan, Y., Luebke, D., & Pennline, H. 2012. Efficient theoretical screening of solid sorbents for CO_2 capture applications*. Int. J. Clean and Energy*, 1:1-11.

Duffield, T.F., Rabiee, A.R. & Lean, I.J. 2008. A meta-analysis of the impact of monensin in lactating dairy cattle. Part 2. Production effects. *J. Dairy Sci.* 91: 1347–1360.

Duffield, T.F., Lissemore, K.D., McBride, B.W. & Leslie, K.E. 2009. Impact of hyperketonemia in early lactation dairy cows on health and production. *J. Dairy Sci.* 92: 571–580.

Duguma, G., Mirkena, T., Haile, A., Iñiguez, L., Okeyo, A.M., Tibbo, M., Rischkowsky, B., Sölkner, J. & Wurzinger, M. 2010. Participatory approaches to investigate breeding objectives of livestock keepers. *Livest. Res. Rur. Devel.* 22: Article #64. Accessed on 28 May 2012 at http://www.lrrd.org/lrrd22/4/dayugu22064.htm.

Dunkley, C.S. 2012. Carbon Foot-print of Poultry Production Farms. Livestock and Poultry Environmental Learning Center. Accessed on 17 June 2012 at http://www.extension.org/pages/58813/live-webcast-information.

Dyer, J.A., Vergé, X.P.C., Desjardins, R.L. & Worth, D.E. 2010. The protein-based GHG emission intensity for livestock products in Canada. *J. Sustain. Agric.* 34: 618–629.

Eckard, R.J., Grainger, C. & de Klein, C.A.M. 2010. Options for the abatement of methane and nitrous oxide from ruminant production: A review. *Livest. Sci.* 130: 47–56.

Ellis, J.L., Dijkstra, J., Kebreab, E., Bannink, A., Odongo, N.E., McBride, B.W. & France, J. 2008. Aspects of rumen microbiology central to mechanistic modelling of methane production in cattle. *J. Agric. Sci., Camb.* 146: 213–233.

Ellis, J.L., Bannink, A., France, J., Kebreab, E. & Dijkstra, J. 2010. Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. *Glob. Change Biol.* 16: 3246–3256.

Ellis, J.L., Dijkstra, J., France, J., Parsons, A.J., Edwards, G.R., Rasmussen, S., Kebreab, E. & Bannink, A. 2012a. Effect of high-sugar grasses on methane emissions simulated using a dynamic model. *J. Dairy Sci.* 95: 272–285.

Ellis, J.L., Dijkstra, J., Bannink, A., Kebreab, E., Hook, S.E., Archibeque, S. & France, J. 2012b. Quantifying the effect of monensin dose on the rumen volatile fatty acid profile in high-grain fed beef cattle. *J. Anim. Sci.* doi: 10.2527/jas.2012-3966.

El-Mashad, H.M., van Loon, W.K.P. & Zeeman, G. 2003. A model of solar energy utilisation in the anaerobic digestion of cattle manure. *Biosyst. Eng.* 84: 231–238.

EPA (US Environmental Protection Agency). 2004. National emission inventory – Ammonia emissions from animal husbandry operations. Washington, DC, EPA.

EPA (US Environmental Protection Agency). 2005. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003. EPA 430-R-05-003. Washington, DC, EPA.

EPA (US Environmental Protection Agency). 2006. Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2020. Washington, DC, EPA.

EPA (US Environmental Protection Agency). 2010. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008. Accessed on 27 September 2012 at http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

EPA (US Environmental Protection Agency). 2011. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2009, Washington, DC, EPA. Accessed on 21 July 2011 at http://epa.gov/climatechange/emissions/dayownloads11/US-GHG-Inventory-2011-Complete_Report.pdf.

Erasmus, L.J., Botha, P.M. & Kistner, A. 1992. Effect of yeast culture supplement on production, rumen fermentation, and duodenal nitrogen flow in dairy cows. *J. Dairy Sci.* 75: 305–3065.

Ercanbrack, S.K. & Knight, A.D. 1991. Effects of inbreeding on reproduction and wool production of Rambouillet, Targhee, and Columbia ewes. *J. Anim. Sci.* 69:4 734–4744.

Erickson, G. & Klopfenstein, T. 2010. Nutritional and management methods to decrease nitrogen losses from beef feedlots. *J. Anim. Sci. 88*(E. Suppl.): E172–E180.

Eschenlauer, S.C.P., McKain, N., Walker, N.D., McEwan, N.R., Newbold, C. J. & Wallace, R.J. 2002. Ammonia production by ruminal microorganisms and enumeration, isolation, and characterization of bacteria capable of growth on peptides and amino acids from the sheep rumen. *Appl. Environ. Microbiol.* 68: 4925–4931.

Escrivão, R.J.A., Webb E.C. & Garcês, A.P.J.T. 2009. Effects of 12 hour calf withdrawal on conception rate and calf performance of Bos indicus cattle under extensive conditions. *Trop. Anim. Health Prod.* 41: 135–139.

Eugène, M., Archimede, H. & Sauvant, D. 2004. Quantitative meta-analysis on the effects of defaunation of the rumen on growth, intake and digestion in ruminants. *Livest. Prod. Sci.* 85: 81–97.

Eugène, M., Masse, D., Chiquette, J. & Benchaar, C. 2008. Meta-analysis on the effects of lipid supplementation on methane production in lactating dairy cows. *Can. J. Anim. Sci.* 88: 331–334.

Eugène, M., Martin, C., Mialon, M.M., Krauss, D., Renand, G. & Doreau, M. 2011. Dietary linseed and starch supplementation decreases methane production of fattening bulls. *Anim. Feed Sci. Technol.* 166–167: 330–337.

Evans, R.D., Wallace, M., Shalloo, L., Garrick, D.J. & Dillon, P. 2006. Financial implications of recent declines in reproduction and survival of Holstein-Friesian cows in spring-calving Irish dairy herds. *Agric. Syst.* 89: 165–183.

Fabbri, C., Valli, L., Guarino, M., Costa, A. & Mazzotta, V. 2007. Ammonia, methane, nitrous oxide and particulate matter emissions from two different buildings for laying hens. *Biosystems Eng.* 97: 441–455.

FAO (Food and Agriculture Organization). 2010. Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. Rome, Italy.

FAO (Food and Agriculture Organization). 2011a. Successes and failures with animal nutrition practices and technologies in developing countries. *In* H.P.S. Makkar, ed. Proceedings of the FAO Electronic Conference, FAO Animal Production and Health Proceedings. No. 11. Rome, Italy.

FAO (Food and Agriculture Organization). 2011b. *Quality assurance for animal feed analysis laboratories*. FAO Animal Production and Health Manual No. 14. Rome.

Faulkner, D.B. & Hutjens, M.F. 1989. Nitrates in livestock feed. BCH-5610 Extension Beef Cattle Resource Committee, University of Wisconsin-Extension, Cooperative Extension (http://www.iowabeefcenter.org/Beef percent20Cattle percent20Handbook/Nitrates_Feed.pdf; accessed on 27 May 2012).

Ferraretto, L.F., Crump, P.M. & Shaver, R.D. 2013. Effect of cereal grain type and corn grain harvesting and processing methods on intake, digestion, and milk production by dairy cows through a meta-analysis. *J. Dairy Sci.* 96 :533–550.

Ferris, C.P., Gordon, F.J., Patterson, D.C., Porter, M.G. & Yan, T. 1999. The effect of genetic merit and concentrate proportion in the diet on nutrient utilisation by lactating dairy cows. *J. Agric. Sci.* (Cambridge) 132: 483–490.

Fields, M.W., Mallik, S. & Russell, J.B. 2000. *Fibrobacter succinogenes* S85 ferments ball-milled cellulose as fast as cellobiose until cellulose surface area is limiting. *Appl. Microbiol. Biotechnol.* 54: 570–574.

Fievez, V., Mbanzamihigo, L., Piattoni, F. & Demeyer, D. 2001a. Evidence for reductive acetogenesis and its nutritional significance in ostrich hindgut as estimated from *in vitro* incubations. *J. Anim. Physiol. Anim. Nutr.* 85: 271–280.

Fievez, V., Vandeweghe, A., Vlaemink, B., Mbanzamihigo, L., Carlier, L. & Demeyer, D. 2001b. Effect of N fertilisation rate, energy supplementation and supplementation strategy on effiiency of N utilisation in the sheep rumen. *Arch. Tiernahr.* 55: 183–205.

Finlay, B.J., Esteban, G., Clarke, K.J., Williams, A.G., Embley, T.M. & Hirt, R.P. 1994. Some rumen ciliates have endoymbiotic methanogens. *FEMS Microbiol. Lett.* 117: 157–162.

Firkins, J.L. 1996. Maximizing microbial protein synthesis in the rumen. *J. Nutr.* 126: 1347S–1354S.

Firkins, J.L. 1997. Effects of feeding nonforage fiber sources on site of fiber digestion. *J. Dairy Sci.* 80: 1426–1437.

Firkins, J.L. 2010. Reconsidering rumen microbial consortia to enhance feed efficiency and reduce environmental impact of ruminant livestock produciton systems. *R. Bras. Zootec.* 39: 445–457.

Firkins, J.L. & Yu, Z. 2006. Characterisation and quantification of the microbial populations in the rumen. *In* K. Sejrsen, T. Hvelplund & M.O. Nielsen, eds. *Ruminant Physiology, Digestion, Metabolism and Impact of Nutrition on Gene Expression, Immunology and Stress*, pp. 19–54. Wageningen, The Netherlands, Wageningen Academic Publishers.

Firkins, J.L., Eastridge, M.L., St-Pierre, N.R. & Noftsger, S.M. 2001. Effects of grain variability and processing on starch utilization by lactating dairy cattle. *J. Anim. Sci.* 79(E. Suppl.): E218–E238.

Firkins, J.L., Hristov, A.N., Hall, M.B., Varga, G.A. & St-Pierre, N.R. 2006. Integration of ruminal metabolism in dairy cattle. *J. Dairy Sci.* 89(E. Suppl.):E31–E51.

Firkins, J.L., Yu, Z. & Morrison, M. 2007. Ruminal nitrogen metabolism: Perspectives for integration of microbiology and nutrition for dairy. *J. Dairy Sci.* 90(E. Suppl.): E1–E16.

Fitz-Rodríguez, G., De Santiago-Miramontes, M.A., Scaramuzzi, R.J., Malpaux, B. & Delgadillo, J.A. 2009. Nutritional supplementation improves ovulation and pregnancy rates in female goats managed under natural grazing conditions and exposed to the male effect. *Anim. Reprod. Sci.* 116: 85–94.

Flachowsky, G. 2002. Efficiency of energy and nutrient use in the production of edible protein of animal origin. *J. Appl. Anim. Res.* 22: 1–24.

Flachowsky, G. 2011. Carbon-footprints for food of animal origin, reduction potentials and research need, *Journal of Applied Animal Research* 39: 2–14.

Flachowsky, G. & Lebzien, P. 2012. Effects of phytogenic substances on rumen fermentation and methane emissions: A proposal for a research process. *Anim. Feed Sci. Technol.* 176: 70–77.

Flatt, W.P., Moe, P.W., Munson, A.W. & Cooper, T. 1969. Energy utilisation by high producing dairy cows. 2. Summary of energy balance experiments with lactating Holstein cows. *In* K.L. Blaxter, J. Kielanowski & G. Thorbek, eds. *Energy Metabolism of Farm Animals. Vol. 12*, pp. 235–251. Warsaw, European Association for Animal Production.

Flessa, H. & Blesse, F. 2000. Laboratory estimates of trace gas emissions following surface application and injection of cattle slurry. *J. Environ. Qual.* 29: 262–268.

Foley, P.A., Kenny, D.A., Callan, J.J., Boland, T.M. & O'Mara, F.P. 2009. Effect of dl-malic acid supplementation on feed intake, methane emission, and rumen fermentation in beef cattle. *J. Anim. Sci.* 87: 1048–1057.

Fonty, G. & Chaucheyras-Durand, F. 2006. Effects and modes of action of live yeasts in the rumen. *Biologia* (Bratisl.) 61: 741–750.

Forsberg, C.W., Lovelock, L.K.A., Krumholz, L. & Buchanan-Smith, J.B. 1984. Protease activities of rumen protozoa. *Appl. Environ. Microbiol.* 47: 101–110.

Fortes, M.R.S., Reverter, A., Nagaraj, S.H., Zhang, Y., Jonsson, N.N., Barris, W., Lehnert, S., Boe-Hansen, G.B. & Hawken, R.J. 2011. A single nucleotide polymorphism-derived regulatory gene network underlying puberty in 2 tropical breeds of beef cattle. *J. Anim. Sci.* 89: 1669–1683.

Fox, D.G., Tylutki, P., Tedeschi, L.O., Van Amburg, M.E., Chase, L.E., Pell, A.N., Overton, T.R. & Russel, J.B. 2003. The Net Carbohydrate and Protein System for evaluating herd nutrition and nutrient excretion. Version 5.0. Animal Science Department Mimeo 213. Cornell University, Ithaca, NY.

Fox, R.H., Myers, R.J.K. & Vallis, I. 1990. The nitrogen mineralization rate of legume residues as influenced by their polyphenol, lignin and nitrogen contents. *Plant and Soil* 129: 251–259.

Franzluebbers, A.J. 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. *Soil & Tillage Res.* 83: 120–147.

French, E.A., Bertics, S.J. & Armentano, L.E. 2012. Rumen and milk odd- and branched-chain fatty acid proportins are minimally influenced by ruminal volatile fatty acid infusions. *J. Dairy Sci.* 95: 2015–2026.

Frutos, P., Hervás, G., Giráldez, F.J. & Mantecón, A.R. 2004. Review. Tannins and ruminant nutrition. *Spanish J. Agric. Res.* 2: 191–202.

Fukumoto, Y. 2010. Bioremediational technique of adding nitrite-oxidizing bacteria for reducing N_2O emission during swine manure composting. *In* Manure: Management, Uses and Environmental Impacts, pp. 167–180. Nova Publishing.

Fukumoto, Y. & Inubushi, K. 2009. Effect of nitrite accumulation on nitrous oxide emission and total nitrogen loss during swine manure composting. *Soil Sci. Plant Nutr.* 55: 428–434.

Fukumoto, Y., Suzuki, K., Osada, T., Kuroda, K., Hanajima, D., Yasuda, T. & Haga, K. 2006. Reduction of nitrous oxide emission from pig manure composting by addition of nitrite-oxidizing bacteria. *Environ. Sci. Technol.* 40: 6787–6791.

Funk, D.A. 2006. Major advances in globalization and consolidation of the artificial insemination industry. *J. Dairy Sci.* 89: 1362–1368.

Funston, R.N., Martin, J.L., Larson, D.M. & Roberts, A.J. 2012. Physiology and endocrinology symposium: Nutritional aspects of developing replacement heifers. *J. Anim. Sci.* 90: 1166–1171.

Gado, H.M., Salem, A.Z.M., Robinson, P.H. & Hassan, M. 2009. Influence of exogenous enzymes on nutrient digestibility, extent of ruminal fermentation as well as milk production and composition in dairy cows. *Anim. Feed Sci. Technol.* 154: 36–46.

Galbraith, J.K., Mathison, G.W., Hudson, R.J., McAllister, T.A. & Cheng, K.-J. 1998. Intake, digestibility, methane and heat production in bison, wapiti and white-tailed deer. *Can. J. Anim. Sci.* 78: 681–691.

Garg, M.R., Sherasia, P.L., Bhanderi, B.M., Phondba, B.T., Shelke, S.K. & Makkar, H.P.S. 2012. Effects of feeding nutritionally balanced rations on animal productivity, feed conversion efficiency, feed nitrogen use efficiency, rumen microbial protein supply, parasitic load, immunity and enteric methane emissions of milking animals under field conditions. *Anim. Feed Sci. Technol.* 179:24–35.

Garland, G.M., Suddick, E., Burger, M., Horwath, W.R. & Six, J. 2011. Direct N_2O emissions following transition from conventional till to no-till in a cover cropped Mediterranean vineyard (*Vitis vinifera*). *Agric. Ecosys. Environ.* (in press).

Garnsworthy, P. 2004. The environmental impact of fertility in dairy cows: a modelling approach to predict methane and ammonia emissions. *Anim. Feed Sci. Technol.* 112: 211–223.

Gatel, F. 1994. Protein quality of legume seeds for non-ruminant animals: a literature review. *Anim. Feed Sci. Technol.* 45: 317–348.

Gerber, P., Chilonda, P., Franceschini, G. & Menzi, H. 2005. Geographical determinants and environmental implications of livestock production intensification in Asia. *Biores. Technol.* 96: 263–276.

Gerber, P., Vellinga, T., Opio, C. & Steinfeld, H. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livest. Sci.* 139: 100–108.

Gerber, P., MacLeod, M., Opio, C., Vellinga, T., Falcucci, A., Weiler, V., Tempio, G., Gianni, G. & Dietze, K. 2012. *Greenhouse gas emissions from livestock food chains: a global assessment.* Bratislava, EAAP.

Getachew, T., Gizaw, S., Lemma, S. & Taye, M. 2011. Breeding practices, growth, and carcass potential of fat-tailed Washera sheep breed in Ethiopia. *Trop. Anim. Health. Prod.* 43: 1443–1448.

Giger-Reverdin, S. & Sauvant, D. 2000. Methane production in sheep in relation to concentrate feed composition from bibliographic data. *Cahiers Options Méditerranéennes* 52: 43–46.

Gill, H.S., Shu, Q. & Leng, R.A. 2000. Immunization with *Streptococcus bovis* protects against lactic acidosis in sheep. *Vaccine* 18: 2541–2548.

Gill, M., Smith, P. & Wilkinson, J.M. 2010. Mitigating climate change: the role of domestic livestock. *Animal* 4: 323–333.

Giltrap, D., Li, C. & Saggar, S. 2010. DNDC: A procee-based model of greenhouse gas fluxes from agricultural soils. *Ag. Ecosyst. Environ.* 136: 292–300.

Girard, M., Ramirez, A.A., Buelna, G. & Heitz, M. 2011. Biofiltration of methane at low concentrations representative of the piggery industry – Influence of the methane and nitrogen concentrations. *Chem. Eng. J.* 168: 151–158.

Givens, D.I. & Deaville, E.R. 1999. The current and future role of near infrared reflectance spectroscopy in animal nutrition: a review. *Austr. J. Agric. Res.* 50: 1131–1145.

Gizaw, S., Getachew, T., Tibbo, M., Haile, A. & Dessie, T. 2011. Congruence between selection on breeding values and farmers' selection criteria in sheep breeding under conventional nucleus breeding schemes. *Animal* 5: 995–1001.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. & Toulmin, C. 2011. Food Security: The challenge of feeding 9 billion people. *Science* 327: 812–818.

Goel, G. & Makkar, H.P.S. 2012. Methane mitigation from ruminants using tannins and saponins. *Trop. Anim. Health Prod.* 44: 729–739.

Groff, E.B. & Wu, Z. 2005. Milk production and nitrogen excretion of dairy cows fed different amounts of protein and varying proportions of alfalfa and corn silage. *J. Dairy Sci.* 88: 3619–3632.

González, L.A., Manteca, X., Calsamiglia, S., Schwartzkopf-Genswein, K.S. & Ferret, A. 2012. Ruminal acidosis in feedlot cattle: Interplay between feed ingredients, rumen function and feeding behavior (a review). *Anim. Feed Sci. Technol.* 172: 66–79.

Goodrich, R.D., Garrett, J.E., Gast, D.R., Kirick, M.A., Larson, D.A. & Meiske, J.C. 1984. Influence of monensin on the performance of cattle. *J. Anim. Sci.* 58: 1484–1498.

Gootwine, E. 2011. Mini Review: breeding Awassi and Assaf sheep for diverse management conditions. *Trop. Anim. Health Prod.* 43: 1289–1296.

Gordon, F.J. 1989. Effect of silage additives and wilting on animal performance. In W. Haresign & D.J.A. Cole, eds. *Recent advances in animal nutrition – 1989*, pp. 159–173. London, U.K., Butterworths.

Gould, D.H. 2000. Update on sulfur-related polioencephalomalacia. *Vet. Clin. North Am. Food Anim. Pract.* 16: 481–496.

Grainger C. & Goddard, M.E. 2004. A review of the effects of dairy breed on feed conversion efficiency - an opportunity lost? *Anim. Prod. Aust.* 1: 77–80.

Grainger, C. & Beauchemin, K.A. 2011. Can enteric methane emissions from ruminants be lowered without lowering their production? *Anim. Feed Sci. Technol.* 166–167: 308–320.

Grainger, C., Clarke, T., Beauchemin, K.A., McGinn, S.M. & Eckard, R.J. 2008. Supplementation with whole cottonseed reduces methane emissions and can profitably increase milk production of dairy cows offered a forage and cereal grain diet. *Aust. J. Exp. Agric.* 48: 73–76.

Grainger, C., Clarke, T., Auldist, M.J., Beauchemin, K.A., McGinn, S.M., Waghorn, G.C. & Eckard, R.J. 2009a. Potential use of *Acacia mearnsii* condensed tannins to reduce methane emissions and nitrogen excretion from grazing dairy cows. *Can. J. Anim. Sci.* 89: 241–251.

Grainger, C., Auldist, M.J., O'Brien, G., Macmillan, K.L. & Culley, C. 2009b. Effect of type of diet and energy intake on milk production of Holstein-Friesian cows with extended lactations. *J. Dairy Sci.* 92: 1479–1492.

Grainger, C., Williams, R., Eckard, R.J. & Hannah, M.C. 2010a. A high dose of monensin does not reduce methane emissions of dairy cows offered pasture supplemented with grain. *J. Dairy Sci.* 93: 5300–5308.

Grainger, C., Williams, R., Clarke, T., Wright, A.D. & Eckard, R.J. 2010b. Supplementation with whole cottonseed causes long-term reduction of methane emissions from lactating dairy cows offered a forage and cereal grain diet. *J. Dairy Sci.* 93: 2612–2619.

Grando, S., Baum, M., Ceccarelli, S., Goodchild, A.V., El-Haramein, F.J., Jahoor, A. & Backes, G. 2005. QTLs for straw quality characteristics identified in recombinant inbred lines of a Hordeum vulgare x H. spontaneum cross in a Mediterranean environment. *Theor. Appl. Genet.* 110: 688–695.

Gregorich, E.G., Rochette, P., VandenBygaart, A.J. & Angers, D.A. 2005. Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. Soil Tillage Res. 83:53–72.

Gressley, T.F., Hall, M.B. & Armentano, L.E. 2011. Ruminant Nutrition Symposium: Productivity, digestion, and health responses in hindgut acidosis in ruminants. *J. Anim. Sci.* 89: 1120–1130.

Groffman, P.M., Brumme, R., Butterbach-Bahl, K., Dobbie, K.E., Mosier, A.R., Ojima, D., Papen, H., Parton, W.J., Smith, K.A. & Wagner-Riddle, C. 2000. Evaluating annual nitrous oxide fluxes at the ecosystem scale. *Global Biogeochem. Cycl.* 14: 1061–1070.

Guarino, M., Fabbri, C., Brambilla, M., Valli, L. & Navarotto, P. 2006. Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. *Transactions of the ASABE* 49: 737–747.

Guarino, M., Costa, A. & Porro, M. 2008. Photocatalytic TiO2 coating - to reduce ammonia and greenhouse gases concentration and emission from animal husbandries. *Bioresource Technol.* 99: 2650–2658.

Gillingham, A.G., Ledgard, S.F., Saggar, S., Cameron, K.C., Di, H.J., De Klein, C. and Aspin, M.D. 2012. Initial evaluation of the effects of dyciandiamide (DCD) on nitrous oxide emissions, nitrate leaching and dry matter production from dairy pastures in a range of locations within New Zealand. In L.D. Currie & C.L. Christensen, eds. Advanced nutrient management: gains from the past - goals for the future. Occasional Report No. 25. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Gumen, A., Keskin, A., Yilmazbas-Mecitoglu, G., Karakaya E. & Wiltbank, M.C. 2011. Dry period management and optimization of post-partum reproductive management in dairy cattle. *Reprod. Dom. Anim.* 46(Suppl. 3): 11–17.

Gutierrez-Banuelos, H., Anderson, R.C., Carstens, G.E., Slay, L.J., Ramlachan, N., Horrocks, S.M., Callaway, T.R., Edrington, T.S. & Nisbet, D.J. 2007. Zoonotic bacterial populations, gut fermentation characteristics and methane production in feedlot steers during oral nitroethane treatment and after the feeding of an experimental chlorate product. *Anaerobe* 13:21–31.

Hafner, S.D., Bisogni, J.J. & Jewell, W.J. 2006. Measurement of un-ionized ammonia in complex mixtures. *Environ. Sci. Technol.* 40: 1597–1602.

Hagemann, M., Hemme, T., Ndambi, A., Alqaisi, O. & Sultana, M.N. 2011. Benchmarking of greenhouse gas emissions of bovine milk production systems for 38 countries. *Anim. Feed Sci. Technol.* 166–167:46–58.

Halachmi, I., Børsting, C.F., Maltz, E., Edan, Y. and Weisbjerg, M.R. 2011. Feed intake of Holstein, Danish Red, and Jersey cows in automatic milking systems. *Livest. Sci.* 138: 56–61.

Hales, K.E., Cole, N.A. & MacDonald, J.C. 2012a. Effects of increasing concentrations of wet distillers grains with solubles in steam-flaked corn-based diets on energy metabolism, carbon-nitrogen balance, and methane emissions of cattle. *J. Anim. Sci.* (accepted).

Hales, K.E., Cole, N.A. & MacDonald, J.C. 2012b. Effects of corn processing method and dietary inclusion of wet distillers grains with solubles on energy metabolism, carbon-nitrogen balance, and methane emissions of cattle. J. Anim. Sci. 90:3174–3185.

Halmemies-Beauchet-Filleau, A., Kokkonen, T. Lampi, A.-M., V. Toivonen, V. Shingfield K. J. and A. Vanhatalo. 2011. Effect of plant oils and camelina expeller on milk fatty acid composition in lactating cows fed diets based on red clover silage. *J. Dairy Sci*. 94:4413–4430.

Hammond, K.J., Hoskin, S.O., Burke, J.L., Waghorn, G.C. Koolaard, J.P. & Muetzel, S. 2011. Effects of feeding fresh white clover (*Trifolium repens*) or perennial ryegrass (*Lolium perenne*) on enteric methane emissions from sheep. *Anim. Feed Sci. Technol.* 166–167: 398–404.

Hansen, P.J. & Block, J. 2004. Towards an embryocentric world: the current and potential uses of embryo technologies in dairy production. *Reprod. Fertil. Dev.* 16: 1–14.

Hansen, R., Nielsen, D., Schramm, A., Nielsen, L., Revsbech, N. & Hansen, M. 2009. Greenhouse gas microbiology in wet and dry straw crust covering pig slurry. *J. Environ. Qual.* 38: 1311–1319.

Hao, X., Chang, C. & Larney, F.J. 2004. Carbon, nitrogen balances and greenhouse gas emission during cattle feedlot manure composting. *J. Environ. Qual.* 33: 37–44.

Hao, X., Benke, M.B., Li, C., Larney, F.J., Beauchemin, K.A. & McAllister, T.A. 2011. Nitrogen transformations and greenhouse gas emissions during composting of manure from cattle fed diets containing corn dried distillers grains with solubles and condensed tannins. *Anim. Feed Sci. Technol.* 166–167: 539–549.

Haramoto, E.R. & Gallandt, E.R. 2004. *Brassica* cover cropping for weed management: A review. *Ren. Agric. Food Syst.* 19: 187–198.

Hardin, G. 1968. The Tragedy of the Commons. *Science* 162: 1243–1248.

Hare, E., Norman, H.D. & Wright, J.R. 2006. Survival rates and productive herd life of dairy cattle in the United States. *J. Dairy Sci.* 89:3713–3720.

Harmon, D.L. & McLeod, K.R. 2001. Glucose uptake and regulation by intestinal tissues: implications and whole-body energetics. *J. Anim. Sci.* 79 (E. Suppl.): E59-E72.

Harmon, D.L., Yamka, R.M. & Elam, N.A. 2004. Factors affecting intestinal starch digestion in ruminants: A review. *Can. J. Anim*. Sci. 84: 309–318.

Häring, D.A., Scharenberg, A., Heckendorn, F., Dohme, F., Lüscher, A., Maurer, V., Suter, D. & Hertzberg, H. 2008. Tanniferous forage plants: Agronomic performance, palatability and efficacy against parasitic nematodes in sheep. *Renewable Agric. Food Syst.* 23: 19–29.

Harper, L.A., Sharpe, R.R., Parkin, T.B., de Visscher, A., van Cleemput, O. & Byers, F.M. 2004. Nitrogen cycling through swine production systems: Ammonia, dinitrogen, and nitrous oxide emissions. *J. Environ. Qual.* 33: 1189–1201.

Harris, B.L. & Kolver, E.S. 2001. Review of holsteinization on intensive pastoral dairy farming in New Zealand. *J. Dairy Sci.* 84(E. Suppl.): E56–E61.

Hart, K.J., Martin, P.G., Foley, P.A., Kenny, D.A. & Boland, T.M. 2009. Effect of sward dry matter digestibility on methane production, ruminal fermentation, and microbial populations of zero-grazed beef cattle. *J. Anim. Sci.* 87: 3342–3350.

Hassouna, M., Robin, P., Brachet, A., Palliat, J., Dollé, J. & Faverdin, P. 2010. Development and validation of a simplified method to quantify gaseous emissions from cattle buildings. XVIIth World Congress of the International Commission of Agricultural Engineering (CIGR). Québec City, Canada, 13-17 June 2010.

Hayakawa, A., Akiyama, H., Sudo, S. & Yagi, K. 2009. N_2O and NO emissions from an Andisol field as influenced by pelleted poultry manure. *Soil Biol. Biochem.* 41: 521–529.

He, B.B., Van Gerpen, J.H. & Thompson, J.C. 2009. Sulphur content in selected oils and fats and their corresponding methyl esters. *Appl. Engineering in Agriculture.* 25: 223–226.

Hegarty, R.S., Goopy, J.P., Herd, R.M. & McCorkell, B. 2007. Cattle selected for lower residual feed intake have reduced daily methane production. *J. Anim. Sci.* 85: 1479–1486.

Hegarty, R.S., Alcock, D., Robinson, D.L., Goopy, J.P. & Vercoe, P.E. 2010. Nutritional and flock management options to reduce methane output and methane per unit product from sheep enterprises. *Anim. Prod. Sci.* 50: 1026–1033.

Heichel, G.H. 1987. Legume nitrogen: Symbiotic fixation and recovery by subsequent crops. *In* Z. Heisel, ed. *Energy in Plant Nutrition and Pest Control*, pp. 63–80. New York, NY, Elsevier.

Heller, M.C. & Keoleian, G.A. 2011. Life cycle energy and greenhouse gas analysis of a large-scale vertically integrated organic dairy in the United States. *Environ. Sci. Technol.* 45: 1903–1910.

Henning, P.H., Horn, C.H., Leeuw, K.-J., Meissner, H.H. & Hagg, F.M. 2010. Effect of ruminal administration of the lactate-utilizing strain *Megasphaera elsdenii* (Me) NCIMB 41125 on abrupt or gradual transition from forage to concentrate diets. *Anim. Feed Sci. Technol.* 157: 20–29.

Henry, B. & Eckard, R. 2009. Greenhouse gas emissions in livestock production systems. *Trop. Grasslands* 43: 232–238.

Henry, Y. 1985. Dietary factors involved in feed intake regulation in growing pigs: A review. *Livest. Prod. Sci.* 12: 339–354.

Herd, R.M. & Arthur, P.F. 2009. Physiological basis for residual feed intake. *J. Anim. Sci.* 87: E64–E71.

Hernandez-Ramirez, G., Brouder, S.M., Smith, D.R. & Van Scoyoc, G.E. 2009a. Greenhouse Gas Fluxes in an Eastern Corn Belt Soil: Weather, Nitrogen Source, and Rotation. *J. Environ. Qual.* 38: 841–854.

Hernandez-Ramirez, G., Brouder, S.M., Smith, D.R., Van Scoyoc, G.E. & Michalski, G. 2009b. Nitrous oxide production in an eastern Corn Belt soil: Sources and Redox Range. *Soil Sci. Soc. Am. J.* 73: 1182–1191.

Herrero, M., Murray, I., Fawcett, R.H. & and Dent, J.B. 1996. Prediction of the *in vitro* gas production and chemical composition of kikuyu grass by near-infrared reflectance spectroscopy. *Anim. Feed Sci. Technol.* 66: 51–67.

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C. & Rosegrant, M. 2010. Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems. *Science* 327: 822–825.

Hesse, D. 1994. Comparison of different old and new fattening pig husbandrys with focus on environment and animal welfare. *In* Proceedings of the XII World Congress on Agricultural Engineering, pp. 559–566. Milan.

Hill, D.T., Holmberg, R.D. & Bolte, J.P. 1985. Operating and performance-characteristics of scraped swine manure as a thermophilic anaerobic-digestion substrate. *Agr. Wastes* 14: 37–49.

Hindrichsen, I.K., Wettstein, H.-R., Machmüller, A., Jörg, B. & Kreuzer, M. 2005. Effect of the carbohydrate composition of feed concentrates on methane emission from dairy cows and their slurry. *Environ. Monit. Assess.* 107: 329–350.

Hindrichsen, I.K., Augustsson, E.U., Lund, B., Jensen, M.M., Raun, M., Jatkauskas, J., Vrotniakiene, V. & Ohlsson, C. 2012. Characterisation of different lactic acid bacteria in terms of their oxygen consuming capacity, aerobic stability and pathogen inhibition. In K. Kuoppala, M. Rinne & A. Vanhatalo, eds. Proc. of the XVI Int. Silage Conf. in Hameenlinna, Finland, pp. 105–106. University of Helsinki, MTT Agrifood Research Finland.

Hino, T. & Russell, J.B. 1985. Effect of reducing-equivalent disposal and NADH/NAD on deamination of amino acids by intact rumen microorganisms and their cell extracts. *Appl. Environ. Microbiol.* 50: 1368–1374.

Hironaka, R., Mathison, G.W., Kerrigan, B.K. & Vlach, I. 1996. The effect of pelleting of alfalfa hay on methane production and digestibility by steers. *Sci. Total Environ.* 180: 221–227.

Hoeksma, P., Verdoes, N., Oosthoek, J. & Voermans, J.A.M. 1992. Reduction of ammonia volatilization from pig houses using aerated slurry as recirculation liquid. *Livest. Prod. Sci.* 31: 121–132.

Hoque, M.A. & Suzuki, K. 2008. Genetic parameters for production traits and measures of residual feed intake in Duroc and Landrace pigs. *Anim. Sci. J.* 7: 543–549.

Hollmann, M. & Beede, D.K. 2012. Comparison of effects of dietary coconut oil and animal fat blend on lactational performance of Holstein cows fed a high-starch diet. *J. Dairy Sci.* 95: 1484–1499.

Hollmann, M., Powers, W.J., Fogiel, A.C., Liesman, J.S., Bello, N.M. & Beede, D.K. 2012. Enteric methane emissions and lactational performance of Holstein cows fed different concentrations of coconut oil. *J. Dairy Sci.* 95: 2602–2615.

Holter, J.B., Haves, H.H., Urban, Jr. W.E. & Duthie, A.H. 1992. Energy balance and lactation response in Holstein cows supplemented with cottonseed with or without calcium soap. *J. Dairy Sci.* 75: 1480–1494.

Holtshausen, L., Chaves, A.V., Beauchemin, K.A., McGinn, S.M., McAllister, T.A., Odongo, N.E., Cheeke, P.R. & Benchaar, C. 2009. Feeding saponin-containing Yucca schidigera and *Quillaja saponaria* to decrease enteric methane production in dairy cows. *J. Diary Sci.* 92: 2809–2821.

Holtshausen, L., Chung, Y.-H., Gerardo-Cuervo, H., Oba, M. & Beauchemin, K.A. 2011. Improved milk production efficiency in early lactation dairy cattle with dietary addition of a developmental fibrolytic enzyme additive. *J. Dairy Sci.* 94: 899–907.

Hospido, A. & Sonesson, U. 2005. The environmental impact of mastitis: a case study of dairy herds. *Sci. Total Environ.* 343: 71–82.

Hristov, A.N. 2012**.** Historic, pre-European settlement, and present-day contribution of wild ruminants to enteric methane emissions in the United States. *J. Anim. Sci*. 90:1371-1375.

Hristov, A.N., Huhtanen, P., Rode, L.M., Acharya, S.N. & McAllister, T.A. 2001. Comparison of the ruminal metabolism of nitrogen from ^{15}N-labeled alfalfa preserved as hay or as silage. *J. Dairy Sci.* 84: 2738–2750.

Hristov, A.N., Grandeen, K.L., Ropp, J.K. & McGuire, M.A. 2004. Effect of sodium laurate on ruminal fermentation and utilization of ruminal ammonia nitrogen for milk protein synthesis in dairy cows. *J. Dairy Sci.* 87: 1820–1831.

Hristov, A.N. & Jouany, J.-P. 2005. Factors affecting the efficiency of nitrogen utilization in the rumen. *In* E. Pfeffer & A.N. Hristov, eds. *Nitrogen and Phosphorus Nutrition of Cattle: Reducing the Environmental Impact of Cattle Operations*, pp. 117–166. Wallingford, U.K., CAB International.

Hristov, A.N., Ropp, J.K., Grandeen, K.L., Abedi, S., Etter, R.P., Melgar, A. & Foley, A.E. 2005. Effect of carbohydrate source on ammonia utilization in lactating dairy cows. *J. Anim. Sci.* 83: 408–421.

Hristov, A.N., Hazen, W. & Ellsworth, J.W. 2006. Nitrogen, phosphorus, and potassium balance and potentials for reducing phosphorus imports in Idaho dairy farms. *J. Dairy Sci.* 89: 3702–3712.

Hristov, A.N., Vander Pol, M., Agle, M., Zaman, S., Schneider, C., Ndegwa, P., Vaddella, V.K., Johnson, K., Shingfield, K.J. & Karnati, S.K.R. 2009. Effect of lauric acid and coconut oil on ruminal fermentation, digestion, ammonia losses from manure, and milk fatty acid composition in lactating cows. *J. Dairy Sci.* 92: 5561–5582.

Hristov, A.N., Mertens, D., Zaman, S., Vander Pol, M. & Price, W.J. 2010a. Variability in feed and total mixed ration neutral-detergent fibre and crude protein analyses among commercial laboratories. *J. Dairy Sci.* 93:5348–5362.

Hristov, A.N., Varga, G., Cassidy, T., Long, M., Heyler, K., Karnati, K.R., Corl, B., Hovde, C.J. & Yoon, I. 2010b. Effect of yeast culture on ruminal fermentation and nutrient utilization in dairy cows. *J. Dairy Sci.* 93: 682.692.

Hristov, A.N., Hanigan, M., Cole, A., Todd, R., McAllister, T.A., Ndegwa, P.M. & Rotz, A. 2011a. Ammonia emissions from dairy farms and beef feedlots: A review. *Can. J. Anim. Sci.* 91: 1–35.

Hristov, A.N., Lee, C., Cassidy, T., Long, M., Heyler, L., Corl, B. & Forster, R. 2011b. Effects of lauric and myristic acids on ruminal fermentation, production, and milk fatty acid composition in lactating dairy cows. *J. Dairy Sci.* 94:382–395.

Hristov, A.N., Domitrovich, C., Wachter, A., Cassidy, T., Lee, C., Shingfield, K.J., Kairenius, P., Davis, J. & Brown, J. 2011c. Effect of replacing solvent-extracted canola meal with high-oil traditional canola, high-oleic acid canola, or high-erucic acid rapeseed meals on rumen fermentation, digestibility, milk production, and milk fatty acid composition in lactating dairy cows. *J. Dairy Sci.* 94: 4057–4074.

Hristov, A.N., Lee, C., Cassidy, T., Heyler, K., Tekippe, J.A., Varga, G.A., Corl, B. & Brandt, R.C. 2013. Effect of *Origanum vulgare* L. leaves on production and milk fatty acid composition in lactating dairy cows. *J. Dairy Sci.* 96: 1189-1202.

Hristov, A.N., Lee, C., Hristova, R.A., Huhtanen, P. & Firkins, J. 2012a. A meta-analysis of the variability in continuous culture rumen fermentation and digestibility data. *J. Dairy Sci.* 95: 5299–5307.

Hristov, A.N., Heyler, K., Schurman, E., Griswold, K., Topper, P., Hile, M., Ishler, V., Wheeler, E. & Dinh, S. 2012b. Reducing dietary protein decreased the ammonia emitting potential of manure from commercial dairy farms. *J. Dairy Sci.* 95(Suppl. 2):477(Abstr.).

Hu, W., Liu, J., Wu, Y., Guo, Y. & Ye, J. 2006. Effects of tea saponins on *in vitro* ruminal fermentation and growth performance in growing Boer goat. *Arch. Anim. Nutr.* 60: 89–97.

Huang, W., Kirkpatrick, B.W., Rosa, G.J.M. & Khatib, H. 2010. A genome-wide association study using selective DNA pooling identities candidate markers for fertility in Holstein cattle. *Anim. Genet.* 41:570–578.

Huhtanen, P. & Hristov, A.N. 2009. A meta-analysis of the effects of protein concentration and degradability on milk protein yield and milk N efficiency in dairy cows. *J. Dairy Sci.* 92: 3222–3232.

Huhtanen, P., & Hetta, M. 2012. Comparison of feed intake and milk production responses in continuous and change-over design dairy cow experiments. *Livest. Sci.* 143: 184–194.

Huhtanen, P., Rinne, M. & Nousiainen, J. 2009a. A meta-analysis of feed digestion in dairy cows. 2. The effects of feeding level and diet composition on digestibility. *J. Dairy Sci.* 92: 5031–5042.

Huhtanen, P., Rinne, M. & Nousiainen, J. 2009b. A meta-analysis of feed digestion in dairy cows. 1. The effects of forage and concentrate factors on total diet digestibility. *J. Dairy Sci.* 92: 5019–5030.

Huhtanen, P., Ahvenjärvi, S., Broderick, G.A., Reynal, S.M. & Shingfield, K.J. 2010. Quantifying ruminal digestion of organic matter and neutral detergent fibre using the omasal sampling technique in cattle – a meta analysis. *J. Dairy Sci.* 93:3203–3215.

Hulshof, R.B.A., Berndt, A., Gerrits, W.J.J., Dijkstra, J., van Zijderveld, S.M., Newbold, J.R. & Perdok, H.B. 2012. Dietary nitrate supplementation reduces methane emission in beef cattle fed sugarcane based diets. *J. Anim. Sci.* 90:2317–2323.

Huntington, G.B. 1997. Starch utilization by ruminants: from basics to the bunk. *J. Anim. Sci.* 75:852-867.

Hurtaud, C. & Peyraud, J.L. 2007. Effects of feeding camelina (seeds or meal) on milk fatty acid composition and butter spreadability. *J. Dairy Sci.* 90: 5134–5145.

Husfeldt, A.W., Endres, M.I., Salfer, J.A. & Janni, K.A. 2012. Management and characteristics of recycled manure solids used for bedding in Midwest freestall dairy herds. *J. Dairy Sci.* 95: 2195–2203.

Hutchinson, J.J., Campbell, C.A. & Desjardins, R.L. 2007. Some perspectives on carbon sequestration in agriculture. *Agric. For. Meteor.* 142: 288–302.

Hymes-Fecht, U.C., Broderick, G.A., Muck, R.E. & Grabber, J.H. 2013. Replacing alfalfa or red clover silage with birdsfoot trefoil silage in total mixed rations increases production of lactating dairy cows. *J. Dairy Sci.* 96:460–469.

IAEA (International Atomic Energy Agency). 2008. *Guidelines for sustainable manure management in Asian livestock production systems*. International Atomic Energy Agency. Wagramer Strasse 5 P.O. Box 100 A-1400 Vienna, Austria. http://www-pub.iaea.org/books/IAEABooks/7882/Guidelines-for-Sustainable-Manure-Management-in-Asian-Livestock-Production-Systems.

Immig, I., Demeyer, D., Fiedler, D., Van Nevel, C. & Mbanzamihigo, L. 1996. Attempts to induce reductive acetogenesis into a sheep rumen. *Arch. Anim. Nutr.* 49: 363–370.

Ingold, M., Dietz, H., Schlecht, E. & Buerkert, A. 2012. Effects of biochar and tannin amendments on yields of sweet corn and radish in Oman. *In* E. Tielkes, ed. *Resilience of agricultural systems against crises* (in press). Book of Abstracts, Tropentag, 19-21 September 2012, Göttingen – Witzenhausen, Cuvillier Verlag, Göttingen, Germany.

Insam, H. & Wett, B. 2008. Control of GHG emission at the microbial community level. *Waste Manage.* 28: 699–706.

IPCC (Intergovernmental Panel on Climate Change). 2006a. Chapter 10. Emissions from Livestock and Manure Management. *In* 2006 IPCC Guidelines for National Greenhouse Gas Inventories. *Volume 4: Agriculture, Forestry and Other Land Use*, pp. 10.1–10.87.

IPCC (Intergovernmental Panel on Climate Change). 2006b. Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application. *In* 2006 IPCC Guidelines for National Greenhouse Gas Inventories. *Volume 4: Agriculture, Forestry and Other Land Use*, pp. 11.1–11.54.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team: R.K. Pachauri & A. Reisinger, eds.), p. 104. Geneva, Switzerland, IPCC. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm.

Islam, M., Abe, H., Terada, F., Iwasaki, K. & Tano, R. 2000. Effects of levels of feed intake and inclusion of corn on rumen environment, nutrient digestibility, methane emission and energy and protein utilization by goats fed alfalfa pellets. *Asian-Aust. J. Anim. Sci.* 13: 948–956.

Jansman, A.J.M., Huisman, J. & van der Poel, A.F.B. 1993. Ileal and faecal digestibility in piglets of field beans (*Vicia faba* L.) varying in tannin content. *Anim. Feed Sci. Technol.* 42: 83–96.

Janssen, P.H. 2010. Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. *Anim. Feed Sci. Technol.* 160: 1–22.

Jarecki, M.K., Parkin, T.B., Chan, A.S.K., Kaspar, T.C., Moorman, T.B., Singer, J.W., Kerr, B.J., Hatfield, J.L. & and Jones, R. 2009. Cover crop effects on nitrous oxide emission from a manure-treated Mollisol. *Agric. Ecosyst. Environ.* 134: 29–35.

Jarret, G., Martinez, J. & Dourmad, J.Y. 2011. Effect of biofuel co-products in pig diets on the excretory patterns of N and C and on the subsequent ammonia and methane emissions from pig effluent. *Animal* 5: 622–631.

Jayanegara, A., Togtokhbayar, N., Makkar, H.P.S & Becker, K. 2009. Tannins determined by various methods as predictors of methane production reduction potential of plants by an *in vitro* rumen fermentation system. *Anim. Feed Sci. Technol.* 150: 230–237.

Jayanegara, A., Leiber, F. & Kreuzer, M. 2012. Meta-analysis of the relationship between dietary tannin level and methane formation in ruminants from *in vivo* and *in vitro* experiments. *Anim. Physiol. Anim. Nutr.* 96: 365–375.

Jenkins, T.C., Wallace, R.J., Moate, P.J. & Mosley, E.E. 2008. Board-Invited Review: Recent advances in biohydrogenation of unsaturated fatty acids within the rumen microbial ecosystem. *J. Anim. Sci.* 86: 397–412.

Jensen, B.B. 1996. Methanogenesis in monogastric animals**.** *Environ. Mon. Assess*. 42:99-112.

Jiang, X., Sommer, S. & Christensen, K. 2011a. A Review of the Biogas Industry in China. *Energ. Policy* 39: 6073–6081.

Jiang, T., Schuchardt, F., Li, G., Guo, R. & Zhao, Y. 2011b. Effect of C/N ratio, aeration rate and moisture content on ammonia and greenhouse gas emission during the composting. *J. Environ. Sci* (China) 23: 1754–1760.

Joblin, K.N. 1999. Ruminal acetogens and their potential to lower ruminant methane emissions. *Austr. J. Agric. Res.* 50: 1307–1313.

Johnson, E.D., Wood, A.S., Stone, J.B. & Moran Jr., E.T. 1972. Some effects of methane inhibition in ruminants (steers). *Can. J. Anim. Sci.* 52: 703–712.

Johnson, K.A., & Johnson, D.E. 1995. Methane emissions from cattle. *J. Anim. Sci.* 73: 2483–2492.

Johnson, L., Harrison, J.H., Hunt, C., Shinners, K., Doggett, C.G. & Sapienza, D. 1999. Nutritive value of corn silage as affected by maturity and mechanical processing: A contemporary review. *J. Dairy Sci.* 82: 2813–2825.

Jones, F.M., Phillips, F.A., Naylor, T. & Mercer, N.B. 2011. Methane emissions from grazing Angus beef cows selected for divergent residual feed intake. *Anim. Feed Sci. Technol.* 166–167: 302–307.

Jones, R.J. & Lowry, J.B. 1984. Australian goats detoxify the goitrogen 3-hydroxy-4(1H)pyridone (DHP) after rumen infusions from an Indonesian goat. *Experientia*. 40: 1435–1436.

Jones, R.J. & Megarrity, R.G. 1986. Successful transfer of DHP-degrading bacteria from Hawaiian goats to Australian ruminants to overcome the toxicity of Leucaena. *Aust. Vet. J*. 63: 259–262.

Jouany, J.P., Demeyer, D.I. & Grain, J. 1988. Effect of defaunating the rumen. *Anim. Feed Sci. Technol.* 21: 229–265.

Jung, H.G. & Allen, M.S. 1995. Characteristics of plant cell walls affecting intake and digestibility of forages by ruminants. *J. Anim. Sci.* 73: 2774–2790.

Jungbluth, T. & W. Büscher, W. 1996. Reduction of ammonia emissions from piggeries. In Proceedings of the 1996 ASAE Annual International Meeting, Paper No. 964091, pp.1–16. ASAE, 2950 Niles Rd., St. Joseph, MI 49085-9659 USA.

Jungbluth, T., Hartung, E. & Brose, G. 2001. Greenhouse gas emissions from animal houses and manure stores. *Nutr. Cycl. Agroecosyst.* 60: 133–145.

Kallenbach, C.M., Rolston, D.E. & Horwath, W.R. 2010. Cover cropping affects soil N_2O and CO_2 emissions differently depending on type of irrigation. *Agric. Ecosyst. Environ.* 137: 251–260.

Kannan, A. & Garg, M.R. 2009. Effect of ration balancing on methane emission reduction in lactating animals under field conditions. *Ind. J. Dairy Sci.* 62: 292–296.

Kannan, A., Garg, M.R. & Mahesh, K,B.V. 2011. Effect of ration balancing on milk production, microbial protein synthesis and methane emission in crossbred cows under field conditions in chittoor district of Andhra Pradesh. *Ind. J. Anim. Nutr.* 28: 117–123.

Kariyapperuma, K.A., Furon, A. & Wagner-Riddle, C. 2012. Non-growing season nitrous oxide fluxes from an agricultural soil as affected by application of liquid and composted swine manure. *Can. J. Soil Sci.* 92: 315–327.

Karnati, S.K.R., Yu, Z. & Firkins, J.L. 2009. Investigating unsaturated fat, monensin or bromoethanesulfonate in continuous cultures retaining ruminal protozoa. II. Interaction of treatment and presence of protozoa on prokaryotic communities. *J. Dairy Sci.* 92:3861–3873.

Kaspar, H.F. & Tiedje, J.M. 1981. Dissimilatory reduction of nitrate and nitrite in the bovine rumen: nitrous oxide production and effect of acetylene. *Appl. Environ. Microbiol.* 41: 705–709.

Kassama, A., Friedrich, T., Derpsch, R., Lahmar, R., Mrabet, R., Basch, G., González-Sánchez, E.J. & Serra, R. 2012. Conservation agriculture in the dry Mediterranean climate. *Field Crops Res.* 132: 7–17.

Kavoi, M.M., Hoag, D.L. & Pritchett, J. 2010. Measurement of economic efficiency for smallholder dairy cattle in the marginal zones of Kenya. *J. Develop. Agric. Econ.* 2: 122–137.

Keady, T.W.J., Marley, C.M. & Scollan, N.D. 2012. Grass and alternative forage silages for beef cattle and sheep: effects on animal performance. *In* K. Kuoppala, M. Rinne & A. Vanhatalo, eds. Proceedings of the XVI Int. Silage Conf. Hameenlinna, Finland, pp. 152–165. University of Helsinki, MTT Agrifood Research Finland.

Kebreab, E., Clark, L., Wagner-Riddle, C. & France, J. 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. *Can. J. Anim. Sci.* 86: 135–158.

Kelliher, F.M. & Clark, H. 2010. Methane emissions from bison—An historic herd estimate for the North American Great Plains. *Agric. For. Met.* 150:473–477.

Kelliher, F.M., Clough, T.J., Clark, H. & Rys, G. 2008. Temperature dependence of dicyandiamide (DCD) degradation in soils: A data synthesis. *Soil Biol. Biochem.* 40: 1878–1882.

Kennedy, J., Dillon, P., Faverdin, P., Delaby, L., Buckley, F. & Rath, M. 2001. Investigating the role and economic impact of concentrate supplementation at pasture. *Irish Grassland Assoc. J.* 35: 49–62.

Kennedy, P.M. & Charmley, E. 2012. Methane yields from Brahman cattle fed tropical grasses and legumes. *Anim. Prod. Sci.* 52: 225–239.

Kerr, B.J., Ziemer, C.J., Trabue, S.L., Crouse, J.D. & Parkin, T.B. 2006. Manure composition of swine as affected by dietary protein and cellulose concentrations. *J. Anim. Sci.* 84: 1584–1592.

Keshavarz, K. & Austic, R.E. 2006. The use of low-protein, low-phosphorus, amino acid- and phytase-supplemented diets on laying hen performance and nitrogen and phosphorus excretion. *Poult Sci.* 83:75-83.

Khalil, M.I., Gutser, R. & Schmidhalter, U. 2009. Effects of urease and nitrification inhibitors added to urea on nitrous oxide emissions from a loess soil. *J. Plant Nutr. Soil. Sci.* 172: 651–660.

Khanum, S.A., Hussain, M., Hussain, H.N., Kausar, R., Sadaf, S. & Yaqoob, T. 2010. Assessment of animal productivity and methane production using an associative feeding strategy. *In* Improving Livestock Production Using Indigenous Resources and Conserving the Environment (IAEA-TECDOC-1640), pp. 25–33. Vienna, Austria, International Atomic Energy Agency.

Kim, M., Ahn, Y.H. & Speece, R.E. 2002. Comparative process stability and efficiency of anaerobic digestion; mesophilic vs thermophilic. *Water Res.* 36: 4369–4385.

Kingston-Smith, A.H., Edwards, J.E., Huws, S.A., Kim, E.J. & Abberton, M. 2010. Plant-based strategies towards minimising 'livestock's long shadow'. *Proc. Nut. Soc.* 69: 613–620.

Kirkwood, R.N. & Aherne, F.X. 1985. Energy intake, body composition and reproductive performance of the gilt. *J. Anim. Sci.* 60: 1518–1529.

Kirkwood, R.N. & Thacker, P.A. 1992. Management of replacement breeding animals. *Vet. Clin. North Am. Food Anim. Pract.* 8: 575–587.

Klevenhusen, F., Kreuzer, M. & Soliva, C.R. 2011. Enteric and manure-derived methane and nitrogen emissions as well as metabolic energy losses in cows fed balanced diets based on maize, barley or grass hay. *Animal* 5: 450–461.

Klieve, A.V., Hennessy, D., Ouwerkerk, D., Forster, R.J., Mackie, R.I. & Attwood, G.T. 2003. Establishing populations of *Megasphaera elsdenii* YE 34 and *Butyrivibrio fibrisolvens* YE 44 in the rumen of cattle fed high grain diets. *J. Appl. Microbiol.* 95: 621–630.

Klusmeyer, T.H., Fitzgerald, A.C., Fabellar, A.C., Ballam, J.M., Cady, R.A. & Vicini, J.L. 2009. Effect of recombinant bovine somatotropin and a shortened or no dry period on the performance of lactating dairy cows. *J. Dairy Sci.* 92: 5503–5511.

Knight, T., Ronimus, R.S., Dey, D., Tootill, C., Naylor, G., Evans, P., Molano, G., Smith, A., Tavendale, M., Pinares-Patino, C.S. & Clark, H. 2011. Chloroform decreases rumen methanogenesis and methanogen populations without altering rumen function in cattle. *Anim. Feed Sci. Technol.* 166: 101–112.

Kolver, E.S. & Aspin, P.W. 2006. Supplemental fumarate did not influence milksolids or methane production from dairy cows fed high quality pasture. *Proc. N.Z. Soc. Anim. Prod.* 66: 409–415.

Kolver, E.S., Roche, J.R., Burke, C.R., Kay, J.K. & Aspin, P.W. 2008. Extending lactation in pasture-based dairy cows: 1. Genotype and diet effect on milk and reproduction. *J. Dairy Sci.* 90: 5518–5530.

Korver, S. 1988. Genetic aspects of feed intake and feed efficiency in dairy cattle: a review. *Livest. Prod. Sci.* 20: 1–13.

Kovacevic, V. & Wesseler, J. 2010. Cost-effectiveness analysis of algae energy production in the EU. *Energ. Policy* 38: 5749–5757.

Krehbiel, C.R., Rust, S.R., Zhang, G. & Gilliland, S.E. 2003. Bacterial direct-fed microbials in ruminant diets: Performance response and mode of action. *J. Anim. Sci.* 81(E. Suppl. 2): E120–E132.

Kristensen, T., Mogensen, L., Knudsen, M.T. & Hermansen, J.E. 2011. Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach. *Livest. Sci.* 140: 136–148.

Krueger, N.A., Adesogan, A.T., Staples, C.R., Krueger, W.K., Kim, S.C., Littell, R.C. & Sollenberger, L.E. 2008. Effect of method of applying fibrolytic enzymes or ammonia to Bermudagrass hay on feed intake, digestion, and growth of beef steers. *J. Anim. Sci.* 86: 882–889.

Külling, D.R., Menzi, H., Sutter, F., Lischer, P. & Kreuzer, M. 2003. Ammonia, nitrous oxide and methane emissions from differently stored dairy manure derived from grass- and hay-based rations. *Nutr. Cycling Agroecosyst.* 65: 13–22.

Külling, D.R., Menzi, H., Krober, T.F., Neftel, A., Sutter, F., Lischer, P. & Kreuzer, M. 2001. Emissions of ammonia, nitrous oxide and methane from different types of dairy manure during storage as affected by dietary protein content. *J. Agri. Sci.* 137: 235–250.

Kuhn, M.T., Hutchison, J.L. & Wiggans, G.R. 2006. Characterization of Holstein heifer fertility in the United States. *J. Dairy Sci.* 89: 4907–4920.

Kurihara, M., Osada, T., Nishida, T., Purnomoadi, A. & Yagi, K. 2009. Global emission rate of nitrous oxide from cattle themselves. http://www.coalinfo.net.cn/coalbed/meeting/2203/papers/agriculture/AG054.pdf.

Lacassagne, L., Francesch, M., Carre, B. & Melcion, J.P. 1988. Utilization of tannin-containing and tannin-free faba beans (*Vicia faba*) by young chicks: effects of pelleting feeds on energy, protein and starch digestibility. *Anim. Feed Sci. Technol.* 20: 59–68.

LaCount, D.W., Drackley, J.K., Cicela, T.M. & Clark, J.H. 1995. High oil corn as silage or grain for dairy cows during an entire lactation. *J. Dairy Sci.* 78: 1745–1754.

Lague, C., Gaudet, E., Agnew, J. & Fonstad, T.A. 2005. Greenhouse gas emissions from liquid swine manure storage facilities in Saskatchewan. *Transactions of the ASAE* 48: 2289–2296.

Lander, C.H., Moffitt, D. & Alt, K. 1998. Nutrients available from livestock manure relative to crop growth requirements. Resource Assessment and Strategic Planning Working Paper 98-1., United States Department of Agriculture, Natural Resources Conservation Service. http://www.nrcs.usda.gov/wps/portal/nrcs/dayetail/national/technical/nra/rca/?&cid=nrcs143_014175.

Langmeier, M., Frossard, E., Kreuzer, M., Mäder, P., Dubois, D., Oberson, A., Recous, S. & Nicolardot, B. 2002. Nitrogen fertilizer value of cattle manure applied on soils originating from organic and conventional farming systems. *Agronomie* 22: 789–800.

Lantz, M., Svensson, M., Bjornsson, L. & Borjesson, P. 2007. The prospects for an expansion of biogas systems in Sweden - Incentives, barriers and potentials. *Energ. Policy* 35: 1830–1843.

Lapierre, H., Lobley, G.E., Ouellet, D.R., Doepel, L. & Pacheco, D. 2007. Amino acid requirements for lactating dairy cows: Reconciling predictive models and biology. *In* Proceedings of Cornell Nutrition Conference, pp. 39–59. Dept. of Animal Science,Cornell University, Syracuse, NY.

Lapierre, H., Ouellet, D.R., Doepel, L., Holtrop, G. & Lobley, G.E. 2008. Histidine, Lysine and Methionine: from metabolism to balanced dairy rations. 44th Eastern Nutrition Conference of the Animal Nutrition Association of Canada (ANAC), University of Guelph, Guelph, Canada, May 22-23, 2008, pp. 19–36.

Lassey, K.R. 2007. Livestock methane emission: From the individual grazing animal through national inventories to the global methane cycle. *Agric. Forest Meteorol.* 142: 120–132.

Lassey, K.R., Walker, C.F., McMillan, A.M.S. & Ulyatt, M.J. 2001. On the performance of SF_6 permeation tubes used in determining methane emission from grazing livestock. *Chemosphere – Global Change Science* 3: 367–376.

Lassey, K.R., Pinares-Patiño, C.S., Martin, R.J., Molano, G. & McMillan, A.M.S. 2011. Enteric methane emission rates determined by the SF_6 tracer technique: Temporal patterns and averaging periods. *Anim. Feed Sci. Technol.* 166–167: 183–191.

Latshaw, D.J. & L. Zhao. 2011. Dietary protein effects on hen performance and nitrogen excretion. *Poult. Sci.* 90:99-106.

Le Van, T.D., Robinson, J.A., Ralph, J., Greening, R.C., Smolenski, W.J., Leedle, J.A.Z. & Schaeffer, D.M. 1998. Assessment of reductive acetogenesis with indigenous ruminal bacterium populations and *Acetitomaculum ruminis*. *Appl. Environ. Microbiol.* 64: 3429–3436.

Leahy, S.C., Kelly, W.J., Altermann, E., Ronimus, R.S., Yeoman, C.J., Pacheco, D.M., Li, D., Kong, Z., McTavish, S., Sang, C., Lambie, S.C., Janssen, P.H., Dey, D. & Attwood, G.T. 2010. The genome sequence of the rumen *Methanogen Methanobrevibacter* reveals new possibilities for controlling ruminant methane emissions. *PLoS ONE* 5: e8926. doi:10.1371/journal.pone.0008926.

LeBlanc, S.J., Lissemore, K.D., Kelton, D.F., Duffield, T.F. & Leslie, K.E. 2006. Major advances in disease prevention in dairy cattle. *J. Dairy Sci.* 89: 1267–1279.

Lee, C., Hristov, A.N., Hyler, K.S., Cassidy, T.W., Long, M., Corl, B.A. & Karnati, S.K.R. 2011a. Effects of dietary protein concentration and coconut oil supplementation on nitrogen utilization and production in dairy cows. *J. Dairy Sci.* 94:5544–5557.

Lee, C., Hristov, A.N., Cassidy, T. & Heyler, K. 2011b. Nitrogen isotope fractionation and origin of ammonia nitrogen volatilized from cattle manure in simulated storage. *Atmosphere* 2: 256–270; doi:10.3390/atmos2030256.

Lee, C., Hristov, A.N., Lapierre, H., Cassidy, T., Heyler, K., Varga, G.A. & Parys, C. 2011c. Effect of dietary protein level and rumen-protected amino acid supplementation on dietary amino acid apparent digestibility and recovery in milk in lactating dairy cows. *J. Dairy Sci.* 94(Suppl. 1): 689 (Abstr.).

Lee, C., Hristov, A.N., Dell, C.J., Feyereisen, G.W., Kaye, J. & Beegle, D. 2012a. Effect of dietary protein concentration on ammonia and greenhouse gas emissions from dairy manure. *J. Dairy Sci.* 95:1930–1941.

Lee, C., Hristov, A.N., Heyler, K.S., Cassidy, T.W., Lapierre, H., Varga, G.A. & Parys, C. 2012b. Effects of metabolizable protein supply and amino acids supplementation on nitrogen utilization, production and ammonia emissions from manure in dairy cows. *J. Dairy Sci.* 95: 5253–5268.

Lee, C., Hristov, A.N., Cassidy, T.W., Heyler, K.S., Lapierre, H., Varga, G.A., de Veth, M.J., Patton, R.A. & Parys, C. 2012c. Rumen-protected lysine, methionine, and histidine increase milk protein yield in dairy cows fed metabolizable protein-deficient diet. *J. Dairy Sci.* 95 :6042–6056.

Lee, C., Feyereisen, G.W., Hristov, A.N., Dell, C. J., Kaye, J. & Beegle, D. 2013. Effect of dietary protein concentration on utilization of dairy manure nitrogen for plant growth, leachate nitrate losses, and ammonia emissions from lysimeters. Proceedings, Greenhouse Gases and Animal Agriculture Conference, June 23-26, 2013, Dublin, Ireland (in press).

Lee, J.M., Woodward, S.L., Waghorn, G.C. & Clark, D.A. 2004. Methane emissions by dairy cows fed increasing proportions of white clover (*Trifolium repens*) in pasture. *Proc. N.Z. Grassl. Assoc.* 66: 151–155.

Lee, J., Park, H. & Choi, W. 2002. Selective photocatalytic oxidation of NH_3 to N_2 on platinized TiO_2 in water. *Environ. Sci. Technol.* 36: 5462–5468.

Lee, K. 2012. Precision feeding system adjusts on-the-fly for moisture content. *Progressive Dairyman*. Accessed on 17 March 2012. http://www.progressivedairy.com/index.php?option=com_content&view=article&id=5278.

Lee, M.J., Schreurs, P.J., Messer, A.C. & Zinder, S.H. 1987. Association of methanogenic bacteria with flagellated protozoa from a termite hindgut. *Curr. Microbiol.* 15: 337–341.

Lenis, N.P. & Jongbloed, A.W. 1999. New technologies in low pollution swine diets: diet manipulation and use of synthetic amino acids, phytase and phase feeding for reduction of nitrogen and phosphorus excretion and ammonia emission - review. *Asian-Austr. J. Anim. Sci*. 12 :305-327.

Leng, R.A. 2008. The potential of feeding nitrate to reduce enteric methane production in ruminants. A report to the department of climate change. Commonwealth Government of Australia, Canberra. http://www.penambulbooks.com.

Leslie, M., Aspin, M. & Clark, H. 2008. Greenhouse gas emissions from New Zealand agriculture: issues, perspectives and industry response. *Austr. J. Exp. Agric.* 48: 1–5.

Lewis, W.D., Bertrand, J.A. & Jenkins, T.C. 1999. Interaction of tallow and hay particle size on ruminal parameters. *J. Dairy Sci.* 82: 1532–1537.

Li, H. & Xin, H. 2010. Lab-scale assessment of gaseous emissions from laying-hen manure storage as affected by physical and environmental factors. *Transactions of the ASABE* 53: 593–604.

Li, K., Inubushi, K. & Sakamoto, K. 2002. Nitrous oxide concentrations in an Andisol profile and emissions to the atmosphere as influenced by the application of nitrogen fertilizers and manure. *Biol. Fertil. Soils* 35: 108–113.

Li, Q., Du, W. & Liu, D. 2008. Perspectives of microbial oils for biodiesel production. *Appl Microbiol. Biotechnol.* 80: 749–756.

Liebig, M.A., Tanaka, D.L. & Gross, J.R. 2010. Fallow effects on soil carbon and greenhouse gas flux in central North Dakota. *Soil Sci. Soc. Am. J.* 74: 358–365.

Lila, Z.A., Mohammed, N., Tatsuoka, N., Kanda, S., Kurokawa, Y. & Itabashi, H. 2004. Effect of cyclodextrin diallyl maleate on methane production, ruminal fermentation and microbes in vitro and *in vivo*. *Anim. Sci. J.* 75: 15–22.

Linn, D.M., & Doran. J.W. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci. Soc. Am. J.* 48: 1267–1272.

Longergan, P. 2007. State-of-the-art embryo technologies in cattle. *Soc. Reprod. Fertil. Suppl.* 64: 315–325.

Lopes, J.C., Shaver, R.D., Hoffman, P.C., Akins, M.S., Bertics, S.J., Gencoglu, H. & Coors, J.G. 2009. Type of corn endosperm influences nutrient digestibility in lactating dairy cows. *J. Dairy Sci.* 92: 4541–4548.

Lopez-Fernandez, S., Diez, J.A., Hernaiz, P., Arce, A., Garcia-Torres, L. & Vallejo, A. 2007. Effects of fertiliser type and the presence or absence of plants on nitrous oxide emissions from irrigated soils. *Nutr. Cycling Agroecosyst.* 78: 279–289.

Lopez-Gatius, F. 2012. Factors of a noninfectious nature affecting fertility after artificial insemination in lactating dairy cows. A review. *Theriogenology* 77: 1029–1041.

Lorenz, M.M., Carbonero, C.H., Smith, L. & Udén, P. 2012. In vitro protein degradation of 38 sainfoin accessions and its relationship to tannin content by different assays. *J. Agric. Food Chem.* 60: 5071–5075.

Lovett, D.K., Bortolozzo, A., Conaghan, P., O'Kiely, P.O. & O'Mara, F.P. 2004. In vitro total and methane gas production as influenced by rate of nitrogen application, season of harvest and perennial rye grass cultivar. *Grass Forage Sci.* 59: 227–232.

Lowry, B.J., McSweeney, C.S. & Palmer, B. 1996. Changing perceptions of the effect of plant phenolics on nutrient supply in the ruminant. *Aust. J. Agric. Res.* 47: 829–842.

Loyon, L., Guiziou, F., Beline, E. & Peu, P. 2007. Gaseous Emissions (NH_3, N_2O, CH_4 and CO_2) from the aerobic treatment of piggery slurry - Comparison with a conventional storage system. *Biosyst. Eng.* 97: 472–480.

Lu, Y.-C., Watkins, K.B., Teasdale, J.R. & Abdul-Baki, A.A. 2000. Cover crops in sustainable food production. *Food Rev. Int.* 16: 121–157.

Luna-Nevarez, P., Bailey, D.W., Bailey, C.C., VanLeeuwen, D.M., Enns, R.M., Silver, G.A., DeAtley, K.L. & Thomas, M.G. 2010. Growth characteristics, reproductive performance, and evaluation of their associative relationships in Brangus cattle managed in a Chihuahuan Desert production system. *J. Anim. Sci.* 88: 1891–1904.

Luo, J., de Klein, C.A.M., Ledgard, S.F. & Saggar, S. 2010. Management options to reduce nitrous oxide emissions from intensively grazed pastures: A review. *Agric. Ecosyst. Environ.* 136: 282–291.

Luo, J., Saggar, S., Bhandral, R., Bolan, N., Ledgard, S., Lindsey, S. & Sun, W. 2008a. Effects of irrigating dairy-grazed grassland with farm dairy effluent on nitrous oxide emissions. *Plant and Soil* 309: 119–130.

Luo, J., Ledgard, S.F. & Lindsey, S.B. 2008b. A test of a winter farm management option for mitigating nitrous oxide emissions from a dairy farm. *Soil Use Mgmt.* 24: 121–130.

Luth, P.R., Germain, P., Lecomte, M., Landrain, B., Li, Y. & Cluzeau, D. 2011. Earthworm effects on gaseous emissions during vermifiltration of pig fresh slurry. *Bioresource Technol.* 102: 3679–3686.

Lynch, J.P., O'Kiely, P., Murphy, R. & Doyle, E. 2012. White-rot fungal digestion of maize stover components harvested at sequential maturities. In K. Kuoppala, M. Rinne & A. Vanhatalo, eds. Proc. of the XVI Int. Silage Conf. Hameenlinna, Finland, pp. 220–221. University of Helsinki, MTT Agrifood Research Finland.

Maag, M. & Vinther, F.P. 1996. Nitrous oxide emission by nitrification and denitrification in different soil types and at different soil moisture contents and temperatures. *Appl. Soil Ecol.* 4: 5–14.

Machmüller, A. 2006. Medium-chain fatty acids and their potential to reduce methanogenesis in domestic ruminants. *Agric. Ecosyst. Environ.* 112: 107–114.

Machmüller, A. & Kreuzer, M. 1999. Methane suppression by coconut oil and associated effects on nutrient and energy balance in sheep. *Can. J. Anim. Sci.* 79: 65–72.

Madalena, F.E. 2008. How sustainable are the breeding programs of the global main stream dairy breeds? - The Latin-American situation. *Livest. Res. Rural Dev.* 20, Article #19. Accessed on 15 March 2012. http://www.lrrd.org/lrrd20/2/mada20019.htm.

Maeda, K., Hanajima, D., Toyoda, S., Yoshida, N., Morioka, R. & Osada, T. 2011. Microbiology of nitrogen cycle in animal manure compost. *Microb. Biotechnol.* 4: 700–709.

Maekawa, M., Beauchemin, K.A. & Christensen, D.A. 2002. Effect of concentrate level and feeding management on chewing activities, saliva production, and ruminal ph of lactating dairy cows. *J. Dairy Sci.* 85: 1165–1175.

Maguire, R.O., Crouse, D.A. & Hodges, S.C. 2007. Diet modification to reduce phosphorus surpluses: A mass balance approach. *J. Environ. Qual.* 36: 1235–1240.

Maia, G.D.N., Day, G.B., Gates, R.S. & Taraba, J.L. 2012a. Ammonia biofiltration and Nitrous Oxide generation during the start-up of gas-phase compost biofilters. *Atmos. Environ.* 46: 659–664.

Maia, G.D.N., Day, G.B., Gates, R.S., Taraba, J.L. & Coyne, M.S. 2012b. Moisture effects on greenhouse gases generation in nitrifying gas-phase compost biofilters. *Water Res.* 46: 3023–3031.

Makkar, H.P.S. 2003. Quantification of tannins in tree foliage. FAO/IAEA Publication. Dordrecht, The Netherlands, H.P.S. Kluwer Academic Publishers.

Makkar, H.P.S. & Singh, B. 1987. Kinetics of urea hydrolysis and binding of ammonia to wheat straw during ammoniation by urea. *J. Dairy Sci.* 70: 1313–1317.

Makkar H.P.S. & Becker, K. 1997. Degradation of quillaja saponins by mixed culture of rumen microbes. *Let. Appl. Microb.* 25: 243–245.

Makkar, H.P.S., Blümmel, M. & Becker, K. 1995. In vittro effects and interactions of tannins and saponins and fate of tannins in rumen. *J. Sci. Food Agric.* 69: 481–493.

Mao, H., Wang, J., Zhou, Y. & Liu, J. 2010. Effects of addition of tea saponins and soybean oil on methane production, fermentation and microbial population in the rumen of growing lambs. *Livest. Sci.* 129: 56–62.

Marett, L.C., Auldist, M.J., Grainger, C., Wales, W.J., Blache, D., Macmillan, K.L. & Leury, B.J. 2011. Temporal changes in plasma concentrations of hormones and metabolites in pasture-fed dairy cows during extended lactation. *J. Dairy Sci.* 94: 5017–5026.

Martin, C., Rouel, J., Jouany, J.P., Doreau, M. & Chilliard, Y. 2008. Methane output and diet digestibility in response to feeding dairy cows crude linseed, extruded linseed, or linseed oil. *J. Anim. Sci.* 86: 2642–2650.

Martin, C., Morgavi, D.P. & Doreau, M. 2010a. Methane mitigation in ruminants: from microbe to the farm scale. *Animal* 4: 351–365.

Martin, C., Koolaard, J., Rochette, Y., Clark, H., Jouany, J.P. & Pinares-Patiño, C.S. 2010b. Effect of release rate of the SF_6 tracer on methane and carbon dioxide emission estimates based on ruminal and breath gas samples. *In* E.J. McGeough & S.M. McGinn, eds. Proc. 4th Int. Conf. Greenhouse Gases Anim. Agric., Banff, AB, Canada.

Martin C., Pomiès, D., Ferlay, A., Rochette, Y., Martin, B., Chilliard, Y., Morgavi, D.P.& Doreau, M. 2011. Methane output and rumen microbiota in dairy cows in response to longterm supplementation with linseed or rapeseed of grass silage- or pasture-based diets. *Proc. N. Z. Soc. Anim. Prod.* 71: 242–247.

Martin, S.A. 1998. Manipulation of ruminal fermentation with organic acids: A review. *J. Anim. Sci.* 76: 3123–3132.

Martinez, J., Guiziou, F., Peu, P. & Gueutier, V. 2003. Influence of treatment techniques for pig slurry on methane emissions during subsequent storage. *Biosyst. Eng.* 85: 347–354.

Masse, D.I., Croteau, F., Patni, N.K. & Masse, L. 2003a. Methane emissions from dairy cow and swine manure slurries stored at 10 °C and 15 °C. *Can. Biosyst. Eng.* 45: 6.1–6.6.

Masse, D.I., Masse, L. & Croteau, F. 2003b. The effect of temperature fluctuations on psychrophilic anaerobic sequencing batch reactors treating swine manure. *Bioresource Technol.* 89: 57–62.

Masse, D.I., Talbot, G. & Gilbert, Y. 2011. On farm biogas production: A method to reduce GHG emissions and develop more sustainable livestock operations. *Anim. Feed Sci. Technol.* 166–167: 436–445.

Mathers, J.C. & Walters, D.E. 1982. Variation in methane production by sheep fed every two hours. *J. Agric. Sci.* 98: 633–638.

Mathew, B., Eastridge, M.L., Oelker, E.R., Firkins, J.L. & Karnati, S.K.R. 2011. Interactions of monensin with dietary fat and carbohydrate components on ruminal fermentation and production responses by dairy cows. *J. Dairy Sci.* 94: 396–409.

McCartney, C.A., Bull, I.B. & Dewhurst, R.J. 2012. Archaeol concentration in total rumen contents of cows offered diets based on ryegrass or white clover. *In* Proceedings of Irish Agricultural Research Forum, p. 19.

McCaughey, W.P., Wittenberg, K. & Corrigan, D. 1999. Impact of pasture type on methane production by lactating beef cows. *Can. J. Anim. Sci.* 79: 221–226.

McCourt, A.R.Y.T., Mayne, S. & Wallace, R.J. 2008. Effect of dietary inclusion of encapsulated fumaric acid on methane production from grazing dairy cows. In Proceedings of British Society of Animal Science Annual Conference. p. 64. British Society of Animal Science, Scarborough, UK.

McDonnell, R., Hart, K.J., Boland, T.M., Kelly, A.K., McGee, M. & Kenny, D.A. Effect of ranking on phenotypic residual feed intake and diet on ruminal methane emissions from beef heifers. *In* Agricultural Research Forum 2009, 12 and 13 March 2009, Tullamore, Co Offaly, Ireland, p. 31.

McGeough, E.J., O'Kiely, P., Hart, K.J., Moloney, A.P., Boland, T.M. & Kenny, D.A. 2010. Methane emissions, feed intake, performance, digestibility, and rumen fermentation of finishing beef cattle offered whole-crop wheat silages differing in grain content. *J. Anim. Sci.* 88: 2703–2716.

McGinn, S.M., Beauchemin, K.A., Coates, T. & Colombatto, D. 2004. Methane emissions from beef cattle: Effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. *J. Anim. Sci.* 82: 3346–3356.

McGinn, S.M., Beauchemin, K.A., Iwaasa, A.D. & McAllister, T.A. 2006. Assessment of the sulphur hexafluoride (SF_6) tracer technique for measuring enteric methane emissions from cattle. *J. Environ. Qual.* 35: 1686–1691.

McGinn, S.M., Chung, Y.-H., Beauchemin, K.A., Iwaasa, A.D. & Grainger, C. 2009. Use of corn distillers' dried grains to reduce enteric methane loss from beef cattle. *Can. J. Anim. Sci.* 89: 409–413.

McMahon, L.R., McAllister, T.A., Berg, B.P., Majak, W., Acharya, S.N., Popp, J.D., Coulman, B.E., Wang, Y. & Cheng, K.-J. 2000. A review of the effects of forage condensed tannins on ruminal fermentation and bloat in grazing cattle. *Can. J. Plant. Sci.* 80: 469–485.

McSweeney, C.S., Makkar, H.P.S. & Reed, J.D. 2003. Modification of rumen fermentation for detoxification of harmful plant compounds. *In* Proceedings of the 6th International Symposium on the Nutrition of Herbivores, pp. 239–268. Merida, Yucatan, Mexico.

McSweeney, C. & Mackie, R. 2012. Micro-organisms and ruminant digestion: state of knowledge, trends and future prospects. Background study paper no. 61, FAO, Rime, Italy.

Meade, G., Pierce, K., O'Doherty, J.V., Mueller, C., Lanigan, G. & McCabe, T. 2011. Ammonia and nitrous oxide emissions following land application of high and low nitrogen pig manures to winter wheat at three growth stages. *Agric. Ecosyst. Environ.* 140: 208–217.

Mekoya A, Oosting, S.J., Fernandez-Rivera, S. & Van der Zijpp, A.J. 2008. Farmers' perceptions about exotic multipurpose fodder trees and constraints to their adoption. *Agrofor. Syst.* 73: 141–153.

Melse, R.W. & Ogink, N.W.M. 2005. Air scrubbing techniques for ammonia and odor reduction at livestock operations: review of on-farm research in the Netherlands. *Trans. ASAE* 48: 2303–2313.

Melse, R.W. & van der Werf, A.W. 2005. Biofiltration for mitigation of methane emission from animal husbandry. *Environ. Sci. Technol.* 39: 5460–5468.

Melse, R.W. & Verdoes, N. 2005. Evaluation of four farm-scale systems for the treatment of liquid pig manure. *Biosyst. Eng.* 92: 47–57.

Melse, R.W. & Timmerman, M. 2009. Sustainable intensive livestock production demands manure and exhaust air treatment technologies. *Biores. Technol.* 100: 5506–5511.

Meluzgi,A., Sirri, F., Tallarico, N. & Franchini, A. 2001. Nitrogen retention and performance of brown laying hens on diets with iVerent protein content and constant concentration of amino acids and energy. *Br. Poul. Sci*. 42:213-217.

Mertens, D.R. 1994. Regulation of forage intake. *In* G.C. Fahey, Jr., M. Collins, D.R. Mertens & L.E. Moser, eds. *Forage Quality, Evaluation, and Utilization*, pp. 450–493. Madison, WI, USA, ASA-CSSA-SSSA,

Messman, M.A., Weiss, W.P. & Erickson, D.O. 1992. Effects of nitrogen fertilization and maturity of bromegrass on nitrogen and amino acid utilization by cows. *J. Anim. Sci.* 70: 566–575.

Messman, M.A., Weiss, W.P. & Koch, M.E. 1994. Changes in total and individual proteins during drying, ensiling, and ruminal fermentation of forages. *J. Dairy Sci.* 77: 492–500.

Miguez, F.E. & Bollero, G.A. 2007. Review of corn yield response under winter cover cropping systems using meta-analytic methods. *Crop Sci.* 45: 2318–2329.

Milani, F.X., Nutter, D. & Thoma, G. 2011. Invited review: Environmental impacts of dairy processing and products: A review. *J. Dairy Sci.* 94: 4243–4254.

Miller, L.A., Moorby, J.M., Davies, D.R., Humphreys, M.O., Scollan, N.D., MacRae, J.C. & Theodorou, M.K. 2001. Increased concentration of water-soluble carbohydrate in perennial ryegrass (*Lolium perenne* L.): milk production from late-lactation dairy cows. *Grass Forage Sci.* 56: 383–394.

Miller, R.H., Kuhn, M.T., Norman, H.D. & Wright, J.R. 2008. Death losses for lactation cows in herds enrolled in Dairy Herd Improvement test plans. *J. Dairy Sci.* 91: 3710–3715.

Mirkena, T., Duguma, G., Willam, A., Wurzinger, M., Haile, A., Rischkowsky, R., Okeyo, A.M., Tibbo, M. & Sölkner, J. 2011. Community-based alternative breeding plans for indigenous sheep breeds in four agro-ecological zones of Ethiopia. *J. Anim. Breed. Genet.* 129: 244–253.

Misselbrook, T.H., Powell, J.M., Broderick, G.A. & Grabber, J.H. 2005a. Dietary manipulation in dairy cattle: laboratory experiments to assess the influence on ammonia emissions. *J. Dairy Sci.* 88: 1765–1777.

Misselbrook, T.H., Brookman, S., Smith, K., Cumby, T., Williams, A. & McCrory, D. 2005b. Crusting of stored dairy slurry to abate ammonia emissions: pilot-scale studies. *J. Environ. Qual.* 34: 411–419.

Mitsumori, M., Shinkai, T., Takenaka, A., Enishi, O., Higuchi, K., Kobayashi, Y., Nonaka, I., Asanuma, N., Denman, S.E. & McSweeney, C.S. 2011. Responses in digestion, rumen fermentation and microbial populations to inhibition of methane formation by a halogenated methane analogue. *Br. J. Nutr.* 8: 1–10.

Mkhabela, M.S., Gordon, R., Burton, D., Madani, A., Hart, W. & Elmi, A. 2006. Ammonia and nitrous oxide emissions from two acidic soils of Nova Scotia fertilized with liquid hog manure mixed with or without dicyandiamide. *Chemosphere* 65: 1381–1387.

Moate, P.J., Williams, S.R.O., Grainger, C., Hannah, M.C., Ponnampalam, E.N. & Eckard, R.J. 2011. Influence of cold-pressed canola, brewers grains and hominy meal as dietary supplements suitable for reducing enteric methane emissions from lactating dairy cows. *Anim. Feed Sci. Technol.* 166–167: 254–264.

Moe, P.W. & Tyrrell, H.F. 1979. Methane production in dairy cows. *J. Dairy Sci.* 62: 1583–1586.

Mohammed, R., McGinn, S.M. & Beauchemin, K.A. 2011. Prediction of enteric methane output from milk fatty acid concentrations and rumen fermentation parameters in dairy cows fed sunflower, flax, or canola seeds. *J. Dairy Sci.* 94: 6057–6068.

Mohammed, R., Stevenson, D.M., Beauchemin, K.A., Muck, R.E. & Weimer, P.J. 2012. Changes in ruminal bacterial community composition following feeding of alfalfa ensiled with a lactic acid bacterial inoculant. *J. Dairy Sci.* 95:328–339.

Molano, G., Knight, T.W. & Clark, H. 2008. Fumaric acid supplements have no effect on methane emissions per unit of feed intake in wether lambs. *Aust. J. Exp. Agr.* 48: 165–168.

Molina-Alcaide, E., Pascual, M.R., Cantalapiedra-Hijar, G., Morales-García, E.Y. & Martín-García, A.I. 2009. Effects of concentrate replacement by feed blocks on ruminal fermentation and microbial growth in goats and single-flow continuous-culture fermenters. *J. Anim. Sci.* 87: 1321–1333.

Moller, H., Sommer, S. & Ahring, B. 2004. Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure. *J. Environ. Qual.* 33: 27–36.

Molodovskaya, M., Singurindy, O., Richards, B.K. & Steenhuis, T.S. 2008. Nitrous oxide from aerated dairy manure slurries: effects of aeration rates and oxic/anoxic phasing. *Bioresource Technol.* 99: 8643–8648.

Monteny, G.J., Bannink, A. & Chadwick, D. 2006. Greenhouse gas abatement strategies for animal husbandry. *Agric. Ecosyst. Environ.* 112: 163–170.

Moraes, L. E, D. Casper, A. B. Strathe, J. G. Fadel, and E. Kebreab. 2013. Predicting enteric methane emissions from dairy cattle using Bayesian methods. In: *Proceedings of the Greenhouse Gases and Animal Agriculture Conference,* Dublin, Ireland (in press).

Morgavi, D.P., Forano, E., Martin, C. & Newbold, C.J. 2010. Microbial ecosystem and methanogenesis in ruminants. *Animal* 4: 1024–1036.

Morgavi, D.P., Martin, C., Jouany, J.-P. & Ranilla, M.J. 2011. Rumen protozoa and methanogenesis: not a simple cause-effect relationship. *Br. J. Nutr.* 107: 388–397.

Mosnier, E.,,van der Werf, H.G.M., Boisy, J. & Dourmad, J.Y. 2011. Evaluation of the environmental implications of the incorporation of feed-use amino acids in the manufacturing of pig and broiler feeds using Life Cycle Assessment. *Animal* 5: 1972-1983.

Mosoni, P., Martin, C., Forano, E. & Morgavi, D.P. 2011. Long-term defaunation increases the abundance of cellulolytic ruminococci and methanogens but does not affect the bacterial and methanogen diversity in the rumen of sheep. *J. Anim. Sci.* 89: 783–791.

Moss, R.A., Givens, D.I. & Garnsworthy, P.C. 1995. The effect of supplementing grass silage with barley on digestibility, in sacco degradability, rumen fermentation and methane production in sheep at two levels of intake. *Anim. Feed Sci. Technol.* 55: 9–33.

Mourits, M.C.M., Galligan, D.T., Dijkhuizen, A.A. & Huirne, R.B.M. 2000. Optimization of dairy heifer management decisions based on production conditions of Pennsylvania. *J. Dairy Sci.* 83: 1989–1997.

Muck, R.E. 1993. The role of silage additives in making high quality silage. *In* Silage Production from Seed to Animal, Proceedings from the National Silage Production Conference, pp. 106–116. Syracuse, NY.

Muck, R.E. 2012. Microbiology of ensiling. In K. Kuoppala, M. Rinne & A. Vanhatalo, eds. Proc. of the XVI Int. Silage Conf. Hameenlinna, Finland, pp. 75–86. University of Helsinki, MTT Agrifood Research Finland.

Muck, R.E., Broderick, G.A., Faciola, A.P., Hymes-Fecht, U.C. 2011. Milk production response to feeding alfalfa silage inoculated with Lactobacillus plantarum. *J. Anim. Sci.* 89(E-Suppl 1): 546.

Mueller-Harvey, I. 2006. Unravelling the conundrum of tannins in animal nutrition and health. A review. *J. Sci. Food Agric.* 86: 2010–2037.

Muller, H.L., Sax, J. & Kirchgessner, M. 1980. Effect of frequency of feeding on energy losses in faeces, urine and methane in nonlactating and lactating cows. *Zeitschrift fur Tierphysiologie, Tierernahrung und Futtermittelkunde* 44: 181–189.

Muñoz, C., Yan, T., Wills, D.A., Murray, S. & Gordon, A.W. 2012. Comparison of the sulphur hexafluoride tracer and respiration chamber techniques for estimating methane emissions and correction for rectum methane output from dairy cows. *J. Dairy Sci.* 95: 3139–3148.

Murray, R.M., Bryant, A.M. & Leng, R.A. 1976. Rates of production of methane in the rumen and large intestine of sheep. *Br. J. Nutr.* 36: 1–14.

Mwenya, B., Santoso, B., Sar, C., Gamo, Y., Kobayashi, T., Arai, I. & Takahashi, J. 2004. Effects of including β1–4 galacto-oligosaccharides, lactic acid bacteria or yeast culture on methanogenesis as well as energy and nitrogen metabolism in sheep. *Anim. Feed Sci. Technol.* 115: 313–326.

Nagaraja, T.G., Newbold, C.J., Van Nevel, C.J. & Demeyer, D.I. 1997. Manipulation of ruminal fermentation. *In* P.N. Hobson & C.S. Stewart, eds. *The Rumen Microbial Ecosystem*, pp. 523–623. London, Blackie Academic and Professional.

Naqvi, S.M.K., Sejian, V. & Karim, S.A. 2012. Effect of feed flushing during summer season on growth, reproductive performance and blood metabolites in Malpura ewes under semiarid tropical environment. *Trop. Anim. Health Prod*. DOI 10.1007/s11250-012-0185-2.

National Pork Board. 2012. Quick Facts: The Pork Industry at a Glance. Publication # 09133-04/12. Des Moines, IA, USA.

National Research Council. 2001. Nutrient Requirements of Dairy Cattle. 7th rev. ed. Natl. Acad. Sci. Washington, DC.

Navarro-Villa, A., O'Brien, M., Lopez, S., Boland, T.M. & O'Kiely, P. 2011. Modifications of a gas production technique for assessing in vitro rumen methane production from feedstuffs. *Anim. Feed Sci. Technol.* 166–167: 163–174.

Ndegwa, P.M., Hristov, A.N., Arogo, J. & Sheffield, R.E. 2008. A review of ammonia emission mitigation techniques for concentrated animal feeding operations. *Biosystems Eng.* 100: 453–469.

Ndegwa, P.M., Hristov, A.N. & Ogejo, J.A. 2011. Ammonia Emission from Animal Manure: Mechanisms and Mitigation Techniques. *In* Z. He, ed. *Environmental Chemistry of Animal Manure*, pp. 107–151. Hauppauge, NY, Nova Science Publishers.

Nelson, N., Steensma, K., Utsumi, S., Beede, D.K., Zimmerman, S. & Zimmerman, P. 2012. Enteric methane emissions by dairy cows grazing temperate pastures. *J. Dairy Sci.* 95(Suppl. 2): 584 (Abstr.).

Newbold, C.J., Lassalas, B. & Jouany, J.P. 1995. The importance of methanogens associated with ciliate protozoa in ruminal methane production in vitro. *Let. Appl. Microbiol.* 21: 230–234.

Newbold, C.J., Wallace, R.J. & McIntosh, F.M. 1996. Mode of action of the yeast *Saccharomyces cerevisiae* as a feed additive for ruminants. *Br. J. Nutr.* 76: 249–261.

Newbold, C.J. & Rode. L.M. 2006. Dietary additives to control methanogenesis in the rumen. *Inter. Cong. Ser.* 1293: 138–147.

Ni, J.Q., Vinkier, C., Coenegrachts, J. & Hendriks, J. 1999. Effect of manure on ammonia emission from a fattening pig house with partly slatted floor. *Livest. Prod. Sci.* 59: 25–31.

Nicolai, R. & Pohl, S. 2004. Covers for Manure Storage Units. South Dakota State University College of Agriculture & Biological Sciences Cooperative Extension Service/USDA. http://pubstorage.sdstate.edu/AgBio_Publications/articles/FS925-D.pdf.

Nielsen, D., Schramm, A. & Revsbech, N. 2010. Oxygen distribution and potential ammonia oxidation in foating liquid manure crusts. *J. Environ. Qual.* 39: 1813–1820.

Niemann, H., Kuhla, B. & Flachowsky, G. 2011. Perspectives for feed efficient animal production. *J. Anim. Sci.* 89: 4344–4363.

Niezen, J.H., Waghorn, T.S., Charleston, W.A.G. & Waghorn, G.C. 1995. Growth and gastrointestinal nematode parasitism in lambs grazing either lucerne (*Medicago sativa*) or sulla (*Hedysarum coronarium*) which contains condensed tannins. *J. Agric. Sci. Camb.* 125: 281–289.

Niezen, J.H., Waghorn, G.C. & Charleston, W.A.G. 1998a. Establishment and fecundity of Ostertagia circumcincta and Trichostrongylus colubriformis in lambs fed lotus (Lotus pedunculatus) or perennial ryegrass (Lolium perenne). *Vet. Parasitol.* 28: 13–21.

Niezen, J.H., Robertson, H.A., Waghorn, G.C. & Charleston, W.A.G. 1998b. Production, faecal egg counts and worm burdens of ewe lambs which grazed six contrasting forages. *Vet. Parasitol.* 80: 15–27.

Niezen, J.H., Waghorn, G.C., Graham, T., Carter, J.L. & Leathwick, D.M. 2002. The effect of diet fed to lambs on subsequent development of *Trichostrongylus colubriformis* larvae in vitro and on pasture. *Vet. Parasitol.* 105: 269–283.

Nishida, T., Eruden, B., Hosoda, K., Matsuyama, H., Xu, C. & Shioya, S. 2007. Digestibility, methane production and chewing activity of steers fed whole-crop round bale corn silage preserved at three maturities. *Anim. Feed Sci. Technol.* 135: 42–51.

Nishino, N. & Wang, C. 2012. Bacteria associated with ensiling fermentation and aerobic stability of total mixed ration silage. *In* K. Kuoppala, M. Rinne, and A. Vanhatalo, eds. Proc. of the XVI International Silage Conference, Hameenlinna, Finland, pp. 109–110. University of Helsinki, MTT Agrifood Research Finland.

Nkrumah, J.D., Li, C., Basarab, J.A., Guercio, S., Meng, Y., Murdoch, B., Hansen, C. & Moore, S.S. 2004. Association of a single nucleotide polymorphism in the bovine leptin gene with feed intake, feed efficiency, growth, feeding behaviour and carcass quality and body composition. *Can. J. Anim. Sci.* 84: 211–219.

Nocek, J.E., Steele, R.L. & Braund, D.G. 1986. Performance of dairy cows fed forage and grain separately versus a total mixed ration. *J. Dairy Sci.* 69: 2140–2147.

Nogueira, G.P. 2004. Puberty in South American Bos indicus (Zebu) cattle. *Anim. Reprod. Sci.* 82–83: 361–372.

Nolan, J.V., Hegarty, R.S., Hegarty, J., Godwin, I.R. & Woodgate, R. 2010. Effects of dietary nitrate on fermentation, methane production and digesta kinetics in sheep. *Anim. Prod. Sci.* 50: 801–806.

Nordheim, H., Volden, H., Fystro, G. & Lunnan, T. 2007. Prediction of in situ degradation characteristics of neutral detergent fibre (aNDF) in temperate grasses and red clover using near-infrared reflectance spectroscopy (NIRS). *Anim. Feed Sci. Technol.* 139: 92–108.

Norman, H.D., Wright, J.R., Hubbard, S.M., Miller, R.H. & Hutchison, J.L. 2009. Reproductive status of Holstein and Jersey cows in the United States. *J. Dairy Sci.* 92: 3517–3528.

Notter, D.R. 2008. Genetic aspects of reproduction in sheep. *Reprod. Dom. Anim.* 43 (Supp. 2): 122–128.

Nousiainen, J., Ahvenjärvi, S., Rinne, M., Hellämäki, M. & Huhtanen, P. 2004. Prediction of indigestible cell wall fraction of grass silage by near infrared reflectance spectroscopy. *Anim. Feed Sci. Technol.* 115: 295–311.

Noziere, P., Glasser, F. & Sauvant, D. 2010. *In vivo* production and molar percentages of volatile fatty acids in the rumen: a quantitative review by an empirical approach. *Animal* 5: 403–414.

Nyakatawa, E.Z., Mays, D.A., Way, T.R., Watts, D.B., Torbert, H.A. & Smith, D.R. 2011. Tillage and fertilizer management effects on soil-atmospheric exchanges of methane and nitrous oxide in a corn production system. *Appl. Environ. Soil Sci.* Volume 2011, Article ID 475370 (doi:10.1155/2011/475370).

O'Brian, D., Shalloo, L., Grainger, C., Buckley, F., Horan, B. & Wallace, M. 2010. The influence of strain of Holstein-Friesian cow and feeding system on greenhouse gas emissions from pastoral dairy farms. *J. Dairy Sci.* 93:3390–3402.

O'Mara, F.P. 2011. The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. *Anim. Feed Sci. Technol.* 166–167: 7–15.

Odongo, N.E., Bagg, R., Vessie, G., Dick, P., Or-Rashid, M.M., Hook, S.E., Gray, J.T., Kebreab, E., France, J. & McBride, B.W. 2007. Long-term effects of feeding monensin on methane production in lactating dairy cows. *J. Dairy Sci.* 90: 1781–1788.

Oenema, O., Wrage, N., Velthof, G.L., van Groenigen, J.W., Dolfing, J. & Kuikman, P.J. 2005. Trends in global nitrous oxide emissions from animal production systems. *Nutr. Cycl. Agroecosyst.* 72: 51–65.

Oldenbroek, J.K. 1986. The performance of Jersey heifers and heifers of larger dairy breeds on two complete diets with different roughage contents. *Livest. Prod. Sci.* 14: 1–14.

Oldenbroek, J.K. 1988. The performance of Jersey cows and cows of larger dairy breeds on two complete diets with different roughage contents. *Livest. Prod. Sci.* 18: 1–17.

Oliveira, S.D., Berchielli, T.T., Reis, R.A., Vechetini, M.E. & Pedreirac, M.S. 2009. Fermentative characteristics and aerobic stability of sorghum silages containing different tannin levels. *Anim. Feed Sci. Technol.* 154: 1–8.

Ominski, K.H., Boadi, D.A. & Wittenberg, K.M. 2006. Enteric methane emissions from backgrounded cattle consuming all-forage diets. *Can. J. Anim. Sci.* 86: 393–400.

Oosting, S.J., Boekholt, H.A., Los, M.H.M. & Leffering, C.P. 1993. Intake and utilization of energy from ammonia treated and untreated wheat straw by steers and wether sheep fed a basal ration of grass pellets and hay. *Anim. Prod.* 57: 227–236.

Oosting, S.J., Vlemmix, P.J.M. & van Bruchem, J. 1994. Effect of ammonia treatment of wheat straw with or without supplementation of potato protein on intake, digestion and kinetics of comminution, rumen degradation and passage in steers. *Br. J. Nutr.* 72: 147–165.

Oosting, S.J., van Bruchem, J. & Chen, X.B. 1995. Intake, digestion and small intestinal protein availability in relation to ammoniation of wheat straw with or without protein supplementation. *Br. J. Nutr.* 74: 247–268.

Oosting, S.J., Mekoya, A., Fernandez-Rivera, S. & van der Zijpp, A.J. 2011. *Sesbania sesban* as a fodder tree in Ethiopian livestock farming systems: Feeding practices and farmers' perceptions of feeding effects on sheep performance. *Livest. Sci.* 139: 135–142.

Osada, T. 2000. The processing of livestock waste through the use of activated sludge - Treatment with intermittent aeration process. *Asian-Aust. J. Anim. Sci.* 13: 698–701.

Osada, T., Kuroda, K. & Yonaga, M. 1995. Reducing nitrous-oxide gas emissions from fill-and-draw type activated-sludge process. *Water Res.* 29: 1607–1608.

Osada, T., Takada, R. & Shinzato, I. 2011. Potential reduction of greenhouse gas emission from swine manure by using a low-protein diet supplemented with synthetic amino acids. *Anim. Feed Sci. Technol.* 166–167: 562–574.

Østergaard, V., Korver, S., Solbu, H., Andersen, B.B., Oldham, J. & Wiktorsson, H. 1990. Main report - E.A.A.P. working group on: Efficiency in the dairy cow. *Livest. Prod. Sci.* 24:287–304.

Owen, E., Smith, T. & Makkar, H. 2012. Successes and failures with animal nutrition practices and technologies in developing countries: A synthesis of an FAO e-conference. *Anim. Feed Sci. Technol.* 174: 211–226.

Owens, F.N., Secrist, D.S., Hill, W.J. & Gill, D.R. 1998. Acidosis in cattle: A review. *J. Anim. Sci.* 76: 275–286.

Pabbi, S. & Dhar, D.W. 2011. Feasibility of algal biomass for biodiesel production. *In* S.K. Bhatnagar, A. Saxena & S. Kraan, eds. *Algae biofuel*, pp. 268–288. Houston, TX, Studium Press LLC.

Pain, B.F., Misselbrook, T.H., Clarkson, C.R. & Rees, Y.J. 1990. Odour and ammonia emissions following the spreading of anaerobically-digested pig slurry on grassland. *Biol. Wastes* 34: 259–267.

Palm, C.A. & Sanchez, P.A. 1991. Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents. *Soil Biol. Biochem.* 23: 83–88.

Palmquist, D.L. & Jenkins, T.C. 1980. Fat in lactation rations: Review. *J. Dairy Sci.* 63: 1–14.

Panetto, J.C., Gutierrez, J.P., Ferraz, J.B., Cunha, D.G. & Golden, B.L. 2010. Assessment of inbreeding depression in a Guzerat dairy herd: effects of individual increase in inbreeding coefficients on production and reproduction. *J. Dairy Sci.* 93: 4902–4912.

Park, K.H., Jeon, J.H., Jeon, K.H., Kwag, J.H. & Choi, D.Y. 2011. Low greenhouse gas emissions during composting of solid swine manure. *Anim. Feed Sci. Technol.* 166–167: 550–556.

Parsons, A.J., Rowarth, J.S. & Rasmussen, S. 2011. High-sugar grasses. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2011,* Volume 6(46): 1–12

Parthasarathy Rao, P. & Hall, A.J. 2003. Importance of crop residues in crop-livestock systems in India and farmers' perceptions of fodder quality in coarse cereals. *Field Crop Res.* 84: 189–198.

Parthasarathy Rao, P. & Blümmel, M. 2010. A note on the response of sheep to differently priced sorghum stover traded concomitantly and implications for the economy of feeding. *Anim. Nutr. Feed Technol.* 10 (Suppl.1): 105–111.

Patton, R.A., Patton, J.R. & Boucher, S.E. 2012. Defining ruminal and total-tract starch degradation for adult dairy cattle using in vivo data. J. Dairy Sci. 95 :765–782.

Patra, A.K. 2010. Meta-analyses of effects of phytochemicals on digestibility and rumen fermentation characteristics associated with methanogenesis. *J. Sci. Food Agric.* 90: 2700–2708.

Paul, J.W. & Beauchamp, E.G. 1996. Soil microbial biomass C, N mineralization, and N uptake by corn in dairy cattle slurry- and urea-amended soils. *Can. J. Soil Sci.* 76: 469–472.

Peigné, J. & Girardin, P. 2004. Environmental impacts of farm-scale composting practices. *Water, Air, Soil Pol.* 153: 45–68.

Pelletier, N., Pirog, R. & Rasmussen, R. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agric. Syst.* 103: 380–389.

Pellikaan, W.F., Hendriks, W.H., Uwimana, G., Bongers, L.J.G.M., Becker, P.M. & Cone, J.W. 2011a. A novel method to determine simultaneously methane production during in vitro gas production using fully automated equipment. *Anim. Feed Sci. Technol.* 168: 196–205.

Pellikaan, W.F., Stringano, E., Leenaars, J., Bongers, L.J.G.M., van Laar-van Schuppen, S., Plant, J. & Mueller-Harvey, I. 2011b. Evaluating effects of tannins on extent and rate of in vitro gas and CH_4 production using an automated pressure evaluation system (APES). *Anim. Feed Sci. Technol.* 166–167: 377–390.

Pelster, D.E., Chantigny, M.H., Rochette, P., Angers, D.A., Rieux, C. & Vanasse, A. 2012. Nitrous oxide emissions respond differently to mineral and organic nitrogen sources in contrasting soil types. *J. Environ. Qual.* 41: 427–435.

Peng, Y. & Harper, A.E. 1970. Amino acid balance and food intake: effect of different dietary amino acid patterns on the plasma amino acid pattern of rats. *J. Nutr.* 100: 429–437.

Perera, B.M.A.O. 2011. Reproductive cycles of buffalo. *Anim. Reprod. Sci.* 124: 194–199.

Pereira, M.N. & Armentano, L.E. 2000. Partial replacement of forage with nonforage fibre sources in lactating cow diets. II. Digestion and rumen function. *J. Dairy Sci.* 83: 2876–2887.

Peters, G.M., Rowley, H.V., Wiedemann, S., Tucker, R., Short, M.D. & Schulz, M. 2010. Red meat production in Australia: Life cycle assessment and comparison with overseas studies. *Environ. Sci. Technol.* 44: 1327–1332.

Petersen, S.O. 1999. Nitrous oxide emissions from manure and inorganic fertilizers applied to spring barley. *J. Environ. Qual.* 28: 1610–1618.

Petersen, S.O. & Sommer, S.G. 2011. Ammonia and nitrous oxide interactions: Roles of manure organic matter management. *Anim. Feed Sci. Technol.* 166–167: 503–513.

Petersen, S.O., Mutegi, J.K., Hansen, E.M. & Munkholm, L.J. 2011. Tillage effects on N_2O emissions as influenced by a winter cover crop. *Soil Biol. Biochem.* 43: 1509–1517.

Petersen, S.O., Andersen, A.J. & Eriksen, J. 2012. Effects of cattle slurry acidification on ammonia and methane evolution during storage. *J. Environ. Qual.* 41:88–94.

Philippe, F.-X., Laitat, M., Canart, B., Farnir, F., Massart, L., Vandenheede, M. & Nicks, B. 2006. Effects of a reduction of diet crude protein content on gaseous emissions from deep-litter pens for fattening pigs. *Anim. Res.* 55: 397–407.

Philippe, F.-X., Laitat, M., Canart, B., Vandenheede, M. & Nicks, B. 2007. Comparison of ammonia and greenhouse gas emissions during the fattening of pigs, kept either on fully slatted floor or deep litter. *Livest. Sci.* 111: 144–152.

Philippe, F.-X., Canart, B., Laitat, M., Wavreille, J., Vandenheede, M., Bartiaux-Thill, N., Nicks, B. & Cabaraux, J.F. 2009. Gaseous emissions from group-housed gestating sows kept on deep litter and offered an ad libitum high-fibre diet. *Agric. Ecosyst. Environ.* 132: 66–73.

Phillips, C.J.C. & Rind, M.I. 2001. The effects of frequency of feeding a total mixed ration on the production and behavior of dairy cows. *J. Dairy Sci.* 84:1979–1987.

Picard, M.L., Uzu, G., Dunnington, E.A. & Siegel, P.B. 1993. Food intake adjustments of chicks: Short term reactions to deficiencies in lysine, methionine and tryptophan. *Br. Poult. Sci.* 34: 737–746.

Pinares-Patiño, C.S., Baumont, R. & Martin, C. 2003. Methane emissions by Charolais cows grazing a monospecific pasture of timothy at four stages of maturity. *Can. J. Anim. Sci.* 83: 769–777.

Pinares-Patiño, C.S., D'hour, P., Jouany, J.P. & Martin, C. 2007. Effects of stocking rate on methane and carbon dioxide emissions from grazing cattle. *Agric. Ecosyst. Environ.* 121: 30–46.

Pinares-Patiño, C.S. & Clark, H. 2008. Reliability of the sulphur hexafluoride tracer technique for methane emission measurement from individual animals: an overview. *Aust. J. Exp. Agric.* 48: 223–229.

Pinares-Patiño, C.S., Lassey, K.R., Martin, R.J., Molano, G., Fernandez, M., MacLean, S., Sandoval, E., Luo, D. & Clark, H. 2010. Validation of the SF_6 tracer technique for estimation of methane emission from sheep using respiration chambers. *In* E.J. McGeough & S.M. McGinn, eds. Proc. of 4th Int. Conf. on Greenhouse Gases and Animal Agriculture, p. 100. Banff, AB, Canada.

Pinedo, P., Risco, C. & Melendez, P. 2011. A retrospective study on the association between different lengths of the dry period and subclinical mastitis, milk yield, reproductive performance, and culling in Chilean dairy cows. *J. Dairy Sci.* 94: 106–115.

Place, S.E. & Mitloehner, F.M. 2010. Invited review: Contemporary environmental issues: A review of the dairy industry's role in climate change and air quality and the potential of mitigation through improved production efficiency. *J. Dairy Sci.* 93: 3407–3416.

Pollok, C. 2008. Options for Greenhouse Gas Mitigation in the UK, April 2008.

Popova, M., Martin, C., Eugène, M., Mialon, M.M., Doreau, M. & Morgavi, D.P. 2011. Effect of fibre- and starch-rich finishing diets on methanogenic Archaea diversity and activity in the rumen of feedlot bulls. *Anim. Feed Sci. Technol.* 166: 113–121.

Poppy, G. D., A. R. Rabiee, I. J. Lean, W. K. Sanchez, K. L. Dorton, and P. S. Morley. 2012. A meta-analysis of the effects of feeding yeast culture produced by anaerobic fermentation of Saccharomyces cerevisiae on milk production of lactating dairy cows. *J. Dairy Sci.* 1588 95: 6027–6041.

Portejoie, S, Dourmad, J.Y., Martinez, J. & Lebreton, Y. 2004. Effect of lowering crude protein on nitrogen excretion, manure composition and ammonia emission from fattening pigs. *Livest. Prod. Sci.* 91:45–55.

Potter, E.L., Muller, R.D., Wray, M.I., Carroll, L.H. & Meyer, R.M. 1986. Effect of monensin on the performance of cattle on pasture or fed harvested forages in confinement. *J. Anim. Sci.* 62: 583–592.

Poulsen, M., Schwab, C., Jensen, B.B., Engberg, R.M., Spang, A., Canibe, N., Hølbetg, O., Milinovich, G., Fragner, L., Schleper, C., Weckwerth, W., Lund, P., Schramm, A. & Urich, T. 2012. Methylotrophic methanogenic Thermoplasmata implicated in reduced methane emissions from bovine rumen. *Nature Commun.* DOI: 10.1038/ncomms2432.

Powell, J.M., Fernández-Rivera, S. & Hofs, S. 1994. Effects of sheep diet on nutrient cycling in mixed farming systems of semi-arid West Africa. *Agric., Ecosyst. Environ.* 48: 263–271.

Powell, J.M., Gourley, C.J.P., Rotz, C.A. & Weaver, D.M. 2010. Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environ. Sci. Pol.* 13: 217–228.

Powell, J.M. & Broderick, G.A. 2011. Trandisciplinary soil science research: Impacts of dairy nutrition on manure chemistry and the environment. *Soil Sci. Soc. Am. J.* 75: 2071–2078.

Powell, J.M., Aguerre, M.J. & Wattiaux, M.A. 2011a. Dietary crude protein and tannin impact dairy manure chemistry and ammonia emissions from incubated soils. *J. Environ. Qual.* 40: 1767–1774.

Powell, J.M., Aguerre, M.J. & Wattiaux, M.A. 2011b. Tannin extracts abate ammonia emissions from simulated dairy barn floors. 2011. *J. Environ. Qual.* 40: 907–914.

Powell, J.M., Jokela, W.E. & Misselbrook, T.H. 2011c. Dairy slurry application method impacts ammonia emission and nitrate leaching in no-till corn silage. *J. Environ. Qual.* 40: 383–392.

Prapaspongsa, T., Christensen, P., Schmidt, J.H. & Thrane, M. 2010a. LCA of comprehensive pig manure management incorporating integrated technology systems. *J. Cleaner Prod.* 18: 1413–1422.

Prapaspongsa, T., Poulsen, T.G., Hansen, J.A. & Christensen, P. 2010b. Energy production, nutrient recovery and greenhouse gas emission potentials from integrated pig manure management systems. *Waste Manag. Res.* 28:411–422.

Preston, T.R. & Leng, R.A. 1984. Supplementation of diets based on fibrous residues and by-products. In *Straw and other fibrous by-products as feed*, pp. 373–413. Amsterdam, Elsevier Press.

Preston, T.R. & Leng, R.A. 1986. *Matching livestock systems to available feed resources*. Addis Ababa, ILCA.

Rabiee, A.R., Breinhild, K., Scott, W., Golder, H.M., Block, E. & Lean, I.J. 2012. Effect of fat additions to diets of dairy cattle on milk production and components: A meta-analysis and meta-regression. *J. Dairy Sci.* 95: 3225–3247.

Raggio, G., Pacheco, D., Berthiaume, R., Lobley, G.E. & Pellerin, D. 2004. Effect of level of metabolizable protein on splanchnic flux of amino acids in lactating dairy cows. *J. Dairy Sci.* 87: 3461–3472.

Ramin, M. & Huhtanen, P. 2013. Effects of dietary and animal factors on methane production: A meta-analysis. *J. Dairy Sci.* (in press).

Randby, Å.T., Weisbjerg, M.R., Nørgaard, P. & Heringstad, B. 2012. Early lactation feed intake and milk yield responses of dairy cows offered grass silages harvested at early maturity stages. *J. Dairy Sci.* 95: 304–317.

Rao, P.P. & Hall, A.J. 2003. Importance of crop residues in crop-livestock systems in India and farmers' perceptions of fodder quality in coarse cereals. *Field Crop Res.* 84: 189–198.

Rastani, R.R., Grummer, R.R., Bertics, S.J., Gümen, A., Wiltbank, M.C., Mashek, D.G. & Schwab, M.C. 2005. Reducing dry period length to simplify feeding transition cows: milk production, energy balance, and metabolic profiles. *J. Dairy Sci.* 88: 1004–1014.

Rath, D. & Johnson, L.A. 2008. Application and commercialization of flow cytometrically sex-sorted semen. *Reprod. Dom. Anim.* 43(Suppl. 2): 338–346.

Razon, L.F. 2009. Alternative crops for biodiesel feedstock. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, No. 056 (doi: 10.1079/PAVSNNR20094056).

Reid, R.L., Jung, G.A. & Thayne, W.V. 1988. Relationships between nutritive quality and fibre components of cool season and warm season forages: A retrospective study. *J. Anim. Sci.* 66: 1275.

Remais, J., Chen, L. & Seto, E. 2009. Leveraging Rural Energy Investment for Parasitic Disease Control: Schistosome Ova Inactivation and Energy Co-Benefits of Anaerobic Digesters in Rural China. *PLoS ONE* 4: e4856.

Reveneau, C., Karnati, S.K.R., Oelker, E.R. & Firkins, J.L. 2012. Interaction of unsaturated fat or coconut oil with monensin in lactating dairy cows fed twelve times daily. I. Protozoal abundance, nutrient digestibility, and microbial protein flow to the omasum. *J. Dairy Sci.* 95: 2046–2060.

Reynal, S.M. & Broderick, G.A. 2005. Effect of dietary level of rumen-degraded protein on production and nitrogen metabolism in lactating dairy cows. *J. Dairy Sci.* 88: 4045–4064.

Reynolds, C.K. & Kristensen, N.B. 2008. Nitrogen recycling through the gut and the nitrogen economy of ruminants: an asynchronous symbiosis. *J. Anim. Sci.* 86(Suppl. 14): E293–E305.

Reynolds, C.K., Cammell, S.B., Humphries, D.J., Beever, D.E., Sutton, J.D. & Newbold, J.R. 2001. Effects of postrumen starch infusion on milk production and energy metabolism in dairy cows. *J. Dairy Sci.* 84:2250–2259.

Richardson, D., Felgate, H., Watmough, N., Thomson, A. & Baggs, E. 2009. Mitigating release of the potent greenhouse gas N_2O from the nitrogen cycle – could enzymic regulation hold the key? *Trends Biotechnol.* 27: 388–397.

Robinson, P.H. & Erasmus, L.J. 2009. Effects of analysable diet components on responses of lactating dairy cows to *Saccharomyces cerevisiae* based yeast products: A systematic review of the literature. *Anim. Feed Sci. Technol.* 149: 185–198.

Robinson, D.L., Goopy, J. & Hegarty, R.S. 2010. Can rumen methane production be predicted from volatile fatty acid concentrations? *Anim. Prod. Sci.* 50: 630–636.

Rochette, P., Angers, D.A., Chantigny, M.H., Bertrand, N. & Cote, D. 2004. Carbon dioxide and nitrous oxide emissions following fall and spring applications of pig slurry to an agricultural soil. *Soil Sci. Soc. Am. J.* 68: 1410–1420.

Rodhe, L., Pell, M. & Yamulki, S. 2006. Nitrous oxide, methane and ammonia emissions following slurry spreading on grassland. *Soil Use Manage.* 22: 229–237.

Röhrmoser, G., Müller, H.L. & Kirchgessner, M. 1983. Energy balance and energy utilization of lactating cows with restricted protein supply and subsequent refeeding. *Zeitschrift für Tierphysiologie, Tierernährung und Futtermittelkunde* 50: 216–224.

Røjen, B.A., Theil, P.K. & Kristensen, N.B. 2011. Effects of nitrogen supply on inter-organ fluxes of urea-N and renal urea-N kinetics in lactating Holstein cows. *J. Dairy Sci.* 94: 2532–2544.

Røjen B.A. & Kristensen, N.B. 2012. Effect of time duration of ruminal urea infusions on ruminal ammonia concentrations and portal-drained visceral extraction of arterial urea-N in lactating Holstein cows. *J. Dairy Sci.* 95: 1395–1409.

Roos, K.F., Martin, J.H. & Moser, M.A. 2004. *AgSTAR Handbook: A manual for developing biogas systems at commercial farms in the United States*; *Second Edition*. US Environmental Protection Agency. EPA-430-B-97-015.

Rothrock, Jr., M.J., Cook, K.L., Warren, J.G., Eiteman, M.A. & Sistani, K. 2010. Microbial mineralization of organic nitrogen forms in poultry litters. *J. Environ. Qual.* 39: 1848–1857.

Rotz, C.A. & Hafner, S. 2011. Whole farm impact of anaerobic digestion and biogas use on a New York dairy farm. ASABE annual international Meeting, 2011 Louisville, Kentucky, August 7-10, 2011. Paper number 1111194.

Rotz, C.A., Montes, F. & Chianese, D.S. 2010. The carbon footprint of dairy production systems through partial life cycle assessment. *J. Dairy Sci.* 93: 1266–1282.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N. & Shiina, T. 2009. A review of life cycle assessment (LCA) on some food products. *J. Food Eng.* 90: 1–10.

Roy, S. & Rangnekar, D.V. 2006. Farmer adoption of urea treatment of cereal straws for feeding of dairy animals: a success in Mithila milkshed, India. *Livest. Res. Rural Dev.* 18. http://www.lrrd.org/lrrd18/8/roy18118.htm.

Rubaek, G.H., Henriksen, K., Petersen, J., Rasmussen, B. & Sommer, S.G. 1996. Effects of application technique and anaerobic digestion on gaseous nitrogen loss from animal slurry applied to ryegrass (*Lolium perenne*). *J. Agric. Sci.* 126: 481–492.

Rufino, M.C., Rowe, E.C., Delve, R.J. & Giller, K.E. 2006. Nitrogen cycling efficiencies through resource-poor African crop–livestock systems. *Agric. Ecosyst. Environ.* 112: 261–282.

Russell, J.B., O'Connor, J.D., Fox, D.G., Van Soest, P.J. & Sniffen, C.J. 1992. A net carbohydrate and protein system for evaluating cattle diets: I. Ruminal fermentation. *J. Anim. Sci.* 70: 3551–3561.

Russell, J.B. & Wallace, R.J. 1997. Energy-yielding and energy-consuming reactions. *In* P.N. Hobson and C.S. Stewart, eds. *The Rumen Microbial Ecosystem*, pp. 246–282. London, U.K., Blackie Academic & Professional.

Russell, J.B. & Houlihan, A.J. 2003. Ionophore resistance of ruminal bacteria and its potential impact on human health. *FEMS Microbiol. Rev.* 27: 65–74.

Saam, H., Powell, J.M., Jackson-Smith, D.B., Bland, W.L. & Posner, J.L. 2005. Use of animal density to estimate manure nutrient recycling ability of Wisconsin dairy farms. *Agric. Syst.* 84: 343–357.

Safley, L.M. & Westerman, P.W. 1994. Low-temperature digestion of dairy and swine manure. *Bioresource Technol.* 47: 165–171.

Saggar, S., Giltrap, D.L., Li, C. & Tate, K.R. 2007. Modelling nitrous oxide emissions from grazed grasslands in New Zealand. *Agric. Ecosyst. Environ.* 119: 205–216.

Saggar, S., Singh, J., Giltrap, D.L., Zaman, M., Luo, J., Rollo, M., Kim, D.-G., Rys, G. & van der Weerden, T.J. 2012. Quantification of reductions in ammonia emissions from fertiliser urea and animal urine in grazed pastures with urease inhibitors for agriculture inventory: New Zealand as a case study. *Sci. Tot. Environ.* (in press).

Saintilan, R., Merour, I., Tribout, T., Bidanel, J., Brossard, L., van Milgen, J. & Gilbert, H. 2012. Sélection pour l'efficacité alimentaire chez le porc en croissance: opportunités et conséquences de l'utilisation de la consommation moyenne journalière résiduelle dans les populations en sélection collective. *J. Rech. Por*. 44: 13-18.

Saleem, M.A.M. 1998. Nutrient balance patterns in African livestock systems. *Agric. Ecosyst. Environ.* 71: 241–254.

Salminen, E., Rintala, J., Härkönen, J., Kuitunen, M., Högmander, H. & Oikari, A. 2001. Anaerobically digested solid poultry slaughterhouse wastes to be used as fertilizer on agricultural soil. *Bioresource Technol.* 78: 81–88.

Sansoucy, R., Aarts, G. & Leng, R.A. 1988. Molasses-urea blocks as a multinutrient supplement for ruminants. In R. Sansoucy, G. Aarts & T.R. Preston (eds). Sugarcane as Feed, vol. 2, pp. 263–278. Proc. of an FAO Expert Consultation held in Santo Domingo, 7-11 July 1986.

Santschi, D.E., Lefebvre, D.M., Cue, R.I., Girard, C.L. & Pellerin, D. 2011. Complete-lactation milk and component yields following a short (35-d) or a conventional (60-d) dry period management strategy in commercial Holstein herds. *J. Dairy Sci.* 94:2302–2311.

Sar, C., Santoso, B., Mwenya, B., Gamo, Y., Kobayashi, T., Morikawa, R., Kimura, K., Mizukoshi, H. & Takahashi, J. 2004. Manipulation of rumen methanogenesis by the combination of nitrate with ß 1-4 galacto-oligosaccharides or nisin in sheep. *Anim. Feed Sci. Techol.* 115: 129–142.

Sarnklong, C., Cone, J.W., Pellikaan, W. & Hendriks, W. 2010. Utilization of rice straw and different treatments to improve its feed value for ruminants: a review. *Asian-Aust. J. Anim. Sci.* 23: 680–692.

Sauer, F.D., Fellner, V., Kinsman, R., Kramer, J.K., Jackson, H.A., Lee, A.J. & Chen, S. 1998. Methane output and lactation response in Holstein cattle with monensin or unsaturated fat added to the diet. *J. Anim. Sci.* 76: 906–914.

Sauer, T.J., Compston, S.R., West, C.P., Hernandez-Ramirez, G., Gbur, E.E. & Parkin, T.B. 2009. Nitrous oxide emissions from a bermudagrass pasture: Interseeded winter rye and poultry litter. *Soil Biol. Biochem.* 41: 1417–1424.

Sauvant, D. & Giger-Reverdin, S. 2009. Modélisation des interactions digestives et de la production de méthane chez les ruminants. *INRA Prod. Anim.* 22: 375–384.

Sauvant, D., Giger-Reverdin, S., Serment, A. & Broudiscou, I. 2011. Influences des régimes et de leur fermentation dans le rumen sur la production de méthane par les ruminants. In M. Doreau, R. Baumont & J.M. Perez, eds. Gaz à effet de serre en élevage bovin: le méthane. Dossier, *INRA Prod. Anim.* 24: 433–446.

Sawyer, M.S., Hoover, W.J. & Sniffen, C.J. 1974. Effects of a ruminal methane inhibitor on growth and energy metabolism in the ovine. *J. Anim. Sci.* 38: 908–914.

Schiere, J.B. 1995. Cattle, straw and system control: a study of straw feeding systems. PhD Diss. Wageningen University, Wageningen, The Netherlands.

Schiere, J.B., Joshi, A.L., Seetharam, A., Oosting, S.J., Goodchild, A.V., Deinum, B. & van Keulen, H. 2004. Grain and straw for whole plant value: Implications for crop management and genetic improvement strategies. *Aust. J. Exp. Agric.* 40: 277–294.

Schingoethe, D.J., Kalscheur, K.F., Hippen, A.R. & Garcia, A.D. 2009. The use of distillers products in dairy cattle diets. *J. Dairy Sci.* 92: 5802–5813.

Schoonmaker, J.P. & Beitz, D.C. 2012. Hydrogen sulphide: synthesis, physiology, roles and pathology associated with feeding cattle maize co-products of the ethanol industry. *In*, Harinder P.S. Makkar, ed., *Biofuel co-products as livestock feed: Opportunities and challenges,* pp. 101–113, FAO, Rome, Italy.

Schönhusen, U., Zitnan, R., Kuhla, S., Jentsch, W., Derno, J. & Voigt, J. 2003. Effects of protozoa on methane production in rumen and hindgut of calves around time of weaning. *Arch. Tiernahr.* 57: 279–295.

Schwartzkopf-Genswein, K.S., Beauchemin, K.A., Gibb, D.J., Crews Jr., D.H., Hickman, D.D., Streeter, M. & McAllister, T.A. 2003. Effect of bunk management on feeding behavior, ruminal acidosis and performance of feedlot cattle: A review. *J. Anim. Sci.* 81: E149–E158.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. & Yu, T.-H. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319: 1238–1240.

Selinger, L.B., Forsberg, C.W. & Cheng, K.-J. 1996. The rumen: A unique source of enzymes for enhancing livestock production. *Anaerobe* 2: 263–284.

Shah, S.B., Workman, D.J., Yates, J., Basden, T.J., Merriner, C.T. & de Graft-Hanson, J. 2011. Coupled biofilter-heat exchanger prototype for a broiler house. *Appl. Eng. Agric.* 27: 1039–1048.

Sharma, Y.C., Singh, B. & Upadhyay, S.N. 2008. Advancements in development and characterization of biodiesel: A review. *Fuel* 87: 2355–2373.

Shaw, A., Hendrickx, G., Gilbert, M., Mattioli, R., Codjia, V., Dao, B., Diall, O., Mahama, C., Sidibé, I. & Wint, W. 2006. Mapping the benefits: a new decision tool for tsetse and trypanosomiasis interventions. Research Report. Department for International Development, Animal Health Programme, Centre for Tropical Veterinary Medicine, University of Edinburgh, UK and Programme Against African Trypanosomiasis, Food and Agriculture Organization of the United Nations, Rome, Italy.

Sherlock, R.R., Sommer, S.G., Khan, R.Z., Wood, C.W., Guertal, E.A., Freney, J.R., Dawson, C.O. & Cameron, K.C. 2002. Emission of ammonia, methane and nitrous oxide from pig slurry applied to a pasture in New Zealand. *J. Environ. Qual.* 31: 1491–1501.

Shewmaker, G.E., Mayland, H.F., Roberts, C.A., Harrison, P.A., Chatterton, N.J. & Sleper, D.A. 2006. Daily carbohydrate accumulation in eight tall fescue cultivars. *Grass and Forage Sci.* 61: 413–421.

Shih, J.C.H. 1987. Ecological benefits of anaerobic-digestion. *Poultry Sci.* 66: 946–950.

Shih, J.C.H. 1993. Recent development in poultry waste digestion and feather utilization - a review. *Poultry Sci.* 72: 1617–1620.

Shook, G.E. 2006. Major advances in determining appropriate selection goals. *J. Dairy Sci.* 89: 1349–1361.

Shu, Q., Bir, S.H., Gill, H.S., Duan, E., Xu, Y., Hiliard, M.A. & Rowe, J.B. 2001. Antibody response in sheep following immunization with Streptococcus bovis in different adjuvants. *Vet. Res. Commun.* 25: 43–54.

Silvestre, F.T., Carvalho, T.S.M., Crawford, P.C., Santos, J.E.P., Staples, C.R., Jenkins, T. & Thatcher, W.W. 2011. Effects of differential supplementation of fatty acids during the peripartum and breeding periods of Holstein cows: II. Neutrophil fatty acids and function, and acute phase proteins. *J. Dairy Sci.* 94: 2285–2301

Sistani, K.R., Jn-Baptiste, M., Lovanh, N. & Cook, K.L. 2011. Atmospheric emissions of nitrous oxide, methane, and carbon dioxide from different nitrogen fertilizers. *J. Environ. Qual.* 40: 1797–1805.

Sliwinski, B.J., Kreuzer, M., Wettstein, H.R. & Machmuller, A. 2002. Rumen fermentation and nitrogen balance of lambs fed diets containing plantextracts rich in tannins and saponins and associated emissions of nitrogen and methane. *Arch. Anim. Nutr.* 56: 379–392.

Smith, D.R., & Owens, P.R. 2010. Impact of time to first rainfall event on greenhouse gas emissions following manure applications. *Commun. Soil Sci. Plan.* 41: 1604–1614.

Smith, K., Cumby, T., Lapworth, J., Misselbrook, T. & Williams, A. 2007b. Natural crusting of slurry storage as an abatement measure for ammonia emissions on dairy farms. *Biosyst. Eng.* 97: 464–471.

Smith, P.H. 1980. Studies of methanogenic bacteria in sludge. Completion report No. EPA-600/2-80-093. NTIS, Springfield, VA 22161.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. & Sirotenko, O. 2007a. Agriculture. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave & L.A. Meyer, eds. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 498–540. Cambridge, United Kingdom, Cambridge University Press.

Sniffen, C.J., Ballard, C.S., Carter, M.P., Cotanch, K.W., Danna, H.M., Grant, R.J., Mandebvu, P., Suekawa, M. & Martin, S.A. 2006. Effects of malic acid on microbial efficiency and metabolism in continuous culture of rumen contents and on performance of mid-lactation dairy cows. *Anim. Feed Sci. Technol.* 127: 13–31.

Soares, M.P., Gaya, L.G., Lorentz, L.H., Batistel, F., Rovadoscki, G.A., Ticiani, E., Zabot, V., Di Domenico, Q., Madureira, A.P. & Pertile, S.F. 2011. Relationship between the magnitude of the inbreeding coefficient and milk traits in Holstein and Jersey dairy bull semen used in Brazil. *Genet. Mol. Res.* 10: 1942–1947.

Solis, J.C., Byers, F.M., Schelling, G.T., Long, C.R. & Greene, L.W. 1988. Maintenance requirements and energetic efficiency of cows of different breed types. *J. Anim. Sci.* 66: 764–773.

Solomon, S., Qin, D., Manning, M., Alley, R.B., Berntsen, T., Bindoff, N.L., Chen, Z., Chidthaisong, A., Gregory, J.M., Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T.F., Whetton, P., Wood, R.A. & Wratt, D. 2007. *In* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller, eds. Technical Summary. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Sommer, S.G., Møller, H.B. & Petersen, S.O. 2001. Reduktion af drivhusgasemission fra gylle og organisk affald ved biogasbehandling [The reduction of greenhouse gases from manure and organic waste using digestion and biogas production]. DJF-rapport nr 31, Tjele, Denmark: Husdyrbrug, Danish Institute of Agricultural Sciences.

Sommer, S.G., Olesen, J.E., Petersen, S.O., Weisbjerg, M.R., Valli, L., Rodhe, L. & Béline, F. 2009. Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones. *Global Change Biol.* 25: 2825–2837.

Sommer, S.G., Søren, O.P., Sørensen, P., Poulsen, H.D. & Møller, H.B. 2007. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. *Nutr. Cycling Agroecosyst.* 78: 27–36.

Sommer, S.G., S.O. Petersen, and H.B. Møller. 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. *Nutr. Cycl. Agroecosyst.* 69: 143–154.

Sommer, S.G., Petersen, S.O. & Sörgard, H. 2000. Greenhouse gas emission from stored livestock slurry. *J. Environ. Qual.* 28: 1610–1618.

Sommer, S.G., Zhang, G.Q., Bannink, A., Chadwick, D., Misselbrook, T., Harison, R., Hutchings, N.J., Menzi, H., Monteny, G.J., Ni, J.Q., Oenema, O. & Webb, J. 2006. Algorithms determining ammonia emission from buildings housing cattle and pigs and from manure stores. *Adv. Agron.* 89: 261–335.

Sørensen, P. & Eriksen, J. 2009. Effects of slurry acidification with sulphuric acid combined with aeration on the turnover and plant availability of nitrogen. *Agriculture, Ecosystems & Environment* 131(3–4): 240–246.

Spiehs, M.J. & Varel, V.H. 2009. Nutrient excretion and odorant production in manure from cattle fed corn wet distillers grains with soluble. *J. Anim. Sci.* 87:2977–2984.

Spiehs, M.J., Whitney, M.H. & Shurson, G.C. 2002. Nutrient database for distiller's dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota. *J. Anim. Sci.* 80: 2639–2645.

Spiehs, M.J., Woodbury, B.L., Tarkalson, D.D., Wienhold, B.J. & Eigenberg, R.A. 2010. Long term effects of annual additions of animal manure on soil chemical, physical, and biological properties in the Great Plains. International Symposium on Air Quality and Manure Management for Agriculture, CD-Rom Proceedings of the 13-16 September 2010 Conference. ASABE Publication Number 711P0510cd.

Spoelstra, S.F. 1991. Chemical and biological additives in forage conservation. *Landbauforsch Völkenrode* 123: 48–70.

Srinivasan, M.S., Bryant, R.B., Callahan, M.P. & Weld, J.L. 2006. Manure management and nutrient loss under winter conditions: A literature review. *J. Soil Water Conserv.* 61: 200–209.

Staerfl, S.M., Zeitz, J.O., Kreuzer, M. & Soliva, C.R. 2012. Methane conversion rate of bulls fattened on grass or maize silage as compared with the IPCC default values, and the long-term methane mitigation efficiency of adding acacia tannin, garlic, maca and lupine. *Agric. Ecosyst. Environ.* 148: 111–120.

Steed, J.Jr. & Hashimoto, A.G. 1994. Methane emissions from typical manure management systems. *Biores. Technol.* 50: 123–130.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. & de Haan, C. 2006. *Livestock's long shadow – Environmental issues and options*. Rome, Italy, Food and Agriculture Organization of the United Nations,.

Stockwell, R. & Bitan, E. 2012. Understanding opportunities and increasing implementation of climate friendly conservation. *J. Soil Water Cons.* 67: 67A–69A.

Storm, I.M.L.D., Hellwing, A.L.F., Nielsen, N.I. & Madsen, J. 2012. Methods for measuring and estimating methane emission from ruminants. *Animals* 2: 160–183.

Stott, A., MacLeod, M. & Moran, D. 2010. Reducing Greenhouse Gas Emissions Through Better Animal Health. Rural Policy Centre, Scottish Agricultural College. http://www.sac.ac.uk/ruralpolicycentre/publs/healthandwellbeing/greenhousegasemissions/.

St-Pierre, N.R. & Thraen, C.S. 1999. Animal grouping strategies, sources of variation, and economic factors affecting nutrient balance on dairy farms. *J. Dairy Sci.* 82(Suppl. 2): 72–83.

Subba Rao, A., Prabhu, U.H., Sampath, S.R. & Oosting, S.J. 1993. Variation in chemical composition and digestibility of finger millet (Eleusine coracana) straw. *In* K. W. Riley, S. C. Gupta, A. Seetharam, and J. N. Mushonga, ed. *Advances in small millets*. pp. 297–307. New Delhi/ Bombay/Calcutta, India, Oxford & IBH Publ. Co.

Sudana, I.B. & Leng, R.A. 1986. Effects of supplementing a wheat straw diet with urea or a urea molasses block and or cottonseed meal on intake and live weight change of lambs. *Anim. Feed Sci. Technol.* 16: 25–35.

Sundradjat, R. 1990. Transformations and uses of digested solid organic residues. Ph.D. Thesis, Rijksuniversiteit Gent.

Sundstøl, F. & Owen, E. 1984. *Straw and other fibrous by-products as feed. Developments in Animal and Veterinary Sciences*. Amsterdam, The Netherlands, Elsevier.

Sutton, A.L., Kephart, K.B., Verstegen, M.W.A., Canh, T.T. & Hobbs, P.J. 1999. Potential for reduction of odorous compounds in swine manure through diet modification. *J. Anim. Sci.* 77: 430–439.

Sutton A.L., Kephardt, K.B., Patterson, J.A., Mumma, R., Kelly, D.T., Bogus, E., Jones, D.D. & Heber, A. 1996. Manipulating swine diets to reduce ammonia and odor emissions. Pages 445-452 in Proc. 1st Int. Conf. Air Pollution from Agric. Operations, Kansas City, MO.

Sutton, J.D., Knight, R., McAllan, A.B. & Smith, R.H. 1983. Digestion and synthesis in the rumen of sheep given diets supplemented with free and protected oils. *Br. J. Nutr.* 49: 419–432.

Svihus, B., Uhlen, A.K. & Harstad, O.M. 2005. Effect of starch granule structure, associated components and processing on nutritive value of cereal starch: A review. *Anim. Feed Sci. Technol.* 122: 303–320.

Sykes, A.R. 1994. Parasitism and production in farm animals. *Anim. Prod.* 59: 155–172.

Tabacco, E., Borreani, G., Crovetto, G.M., Galassi, G., Colombo, D. & Cavallarin, L. 2006. Effect of chestnut tannin on fermentation quality, proteolysis, and protein rumen degradability of alfalfa silage. *J. Dairy Sci.* 89: 4736–4746.

Takahashi, J. 2011. Some prophylactic options to mitigate methane emission from animal agriculture in Japan. *Asian-Aust. J. Anim. Sci.* 24: 285–294.

Takahashi, J., Ikeda, M., Matsuoka, S. & Fujita, H. 1998. Prophylactic effect of L-cysteine to acute and subclinical nitrate toxicity in sheep. *Anim. Feed Sci. Technol.* 74: 273–280.

Talafha, A.Q. & Ababneh, M.M. 2011. Awassi sheep reproduction and milk production: review. *Trop. Anim. Health Prod.* 43: 1319–1326.

Tamminga, S. 1992. Nutrition management of dairy cows as a contribution to pollution control. *J. Dairy Sci.* 75: 345–357.

Tao, J., Schuchardt, F., GuoXue, L., Rui, G. & YuanQiu, Z. 2011. Effect of C/N ratio, aeration rate and moisture content on ammonia and greenhouse gas emission during the composting. *J. Environ. Sci.* 23: 1754–1760.

Tarawali, S., Herrero, M., Descheemaeker, K., Grings, E. & Blümmel, M. 2011. Pathways for sustainable development of mixed crop livestock systems: Taking a livestock and pro-poor approach. *Livest. Sci.* 139: 11–21.

Tas, B.M., Taweel, H.Z., Smit, H.J., Elgersma, A., Dijkstra, J. & Tamminga, S. 2005. Effects of perennial ryegrass cultivars on intake, digestibility, and milk yield in dairy cows. *J. Dairy Sci.* 88: 3240–3248.

Tekippe, J.A., Hristov, A.N., Heyler, K.S., Cassidy, T.W., Zheljazkov, V.D., Ferreira, J.F.S., Karnati, S.K. & Varga, G.A. 2011. Rumen fermentation and production effects of Origanum vulgare L. leaves in lactating dairy cows. *J. Dairy Sci.* 94: 5065–5079.

Tenuta, M., Mkhabela, M., Tremorin, D., Coppi, L., Phipps, G., Flaten, D. & Ominski, K. 2010. Nitrous oxide and methane emission from a coarse-textured grassland soil receiving hog slurry. *Agric. Ecosyst. Environ.* 138: 35–43.

Theodoridou, K., Aufrère, J., Andueza, D., le Morvan, A., Picard, F., Pourrat, J. & Baumont, R. 2012. Effects of condensed tannins in wrapped silage bales of sainfoin (*Onobrychis viciifolia*) on *in vivo* and in situ digestion in sheep. *Animal* 6: 245–253

Terrill, T.H., Douglas, G.B., Foote, A.G., Purchas, R.W., Wilson, G.F. & Barry, T.N. 1992. Effect of condensed tannins upon body growth,wool growth and rumen metabolism in sheep grazing sulla (*Hedysarum coronarium*) and perennial pasture. *J. Agric. Sci. Camb.* 119: 265–273.

Terrill, T.H., Waghorn, G.C., Wolley, D.J., McNabb, W.C. & Barry, T.N. 1994. Assay and digestion of ^{14}C-labelled condensed tannin in the gastro intestinal tract of sheep. *Br. J. Nutri.* 72: 467–477.

Thatcher, W.W., Bilby, T.R., Bartolome, J.A., Silvestre, F., Staples, C.R. & Santos, J.E.P. 2006. Strategies for improving fertility in the modern dairy cow. *Theriogenology* 65: 30–44.

Theurer, C.B. 1986. Grain processing effects on starch utilization by ruminants. *J. Anim. Sci*. 63: 1649–1662.

Theurer, C.B., Huber, J.T., Delgado-Elorduy, A. & Wanderley, R. 1999. Invited review: Summary of steam-flaking corn or sorghum grain for lactating dairy cows. *J. Dairy Sci.* 82: 1950–1959.

Thoma, G., Frank, J., Maxwell C., East, C. & Nutter, D. 2011. National Scan-level Carbon Footprint Study for Production of US Swine. Minneapolis, MN, USA, Minnesota Pork Congress.

Thoma, G., J. Popp, D. Nutter, D. Shonnard, R. Ulrich, M. Matlock, D. S. Kim, Z. Neiderman, N. Kemper, C. East, F. Adom. 2013. Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. Int. Dairy J. 31 (Supplement 1):S3-S14.

Thomet, P., Piccand, V., Schori, F., Troxler, J., Wanner, W. & Kunz, P. 2010. Efficiency of Swiss and New Zealand dairy breeds under grazing conditions on Swiss dairy farms. *Grassland Science in Europe* 15: B1018–1020.

Thompson, A.G., Wagner-Riddle, C. & Fleming, R. 2004. Emissions of N_2O and CH_4 during the composting of liquid swine manure. *Environ. Monit. Assess.* 91: 87–104.

Thompson, R.B. & Meisinger, J.J. 2002. Management factors affecting ammonia volatilization from land-applied cattle slurry in the mid-Atlantic USA. *J. Environ. Qual.* 31: 1329–1338.

Thompson, R.B., Ryden, J.C. & Lockyer, D.R. 1987. Fate of nitrogen in cattle slurry following surface application or injection to grassland. *Eur. J. Soil. Sci.* 38: 689–700.

Thomsen, I.K., Pederson, A.R., Nyord, T. & Petersen, S.O. 2010. Effects of slurry pre-treatment and application technique on short-term N_2O emissions as determined by a new non-linear approach. *Agric. Ecosys. Environ.* 136: 227–235.

Tiemann, T.T., Hincapie, B., Frossard, E., Kreuzer, M. & Hess, H.D. 2009. Effect of supplementing tropical tannin-free and tanniniferous legumes to grass-fed sheep on the utility of their manure as nitrogen fertiliser. *Livest. Res. Rur. Develop.* Volume 21, Article #41. Accessed on 18 May 2012 at http://www.lrrd.org/lrrd21/3/tiem21041.htm.

Tiezzi, F., Maltecca, C., Penasa, M., Cecchinato, A., Chang, Y.M. & Bittante, G. 2011. Genetic analysis of fertility in the Italian Brown Swiss population using different models and trait definitions. *J. Dairy Sci.* 94: 6162–6172.

Tisdale, S.L., Nelson, W.L., Beaton, J.D. & Havlin, J.L. 1993. Chapter 10: Soil acidity and basicity. *Soil Fertility and Fertilizers* (5th edition). New York, Macmillian Publishing.

Titgemeyer, E.C. 1997. Design and interpretation of nutrient digestion studies. *J. Anim. Sci.* 75: 2235–2247.

Titi, H.H. 2003. Evaluation of feeding a fibrolytic enzyme to lactating dairy cows on their lactational performance during early lactation. *Asian-Aust. J. Anim. Sci.* 16: 677–684.

Tomkins, N.W., Colegate, S.M. & Hunter, R.A. 2009. A bromochloromethane formulation reduces enteric methanogenesis in cattle fed grain-based diets. *Anim. Prod. Sci.* 49: 1053–1058.

Torterolo, M., Curbelo, A., Cajarville, C., Repetto, J.L. & Aguerre, M. 2012. Silage process affects chemical composition and digestion site in high moisture sorghum grain. *J. Anim. Sci.* 90(Suppl. 3): 201.

Tribout, T., Caritez, J.C., Gruand, J., Bouffaud, M., Guillouet, P., Billon, Y., Péry, C., Laville, E. & Bidanel, J.P. 2010. Estimation of genetic trends in French Large White pigs from 1977 to 1998 for growth and carcass traits using frozen semen. *J. Anim. Sci.* 88: 2856–2867.

Tyrrell, H.F. & Moe, P.W. 1972. Net energy value for lactation of a high and low concentrate ration containing corn silage. *J. Dairy Sci.* 55: 1106–1112.

Tyrrell, H.F., Thomson, D.J., Waldo, D.R., Goering, H.K. & Haaland, G.L. 1992. Utilization of energy and nitrogen by yearling Holstein cattle fed direct-cut alfalfa or orchardgrass ensiled with formic acid plus formaldehyde. *J. Anim. Sci.* 70: 3163–3177.

Udo, H.M.J., Aklilu, H.A., Phong, L.T., Bosma, R.H., Budisatria, I.G.S., Patil, B.R., Samdup, T. & Bebe, B.O. 2011. Impact of intensification of different types of livestock production in smallholder crop-livestock systems. *Livest. Sci.* 139: 22–30.

Ungerfeld, E.M., Kohn, R.A., Wallace, R.J. & Newbold, C.J. 2007. A meta-analysis of fumarate effects on methane production in ruminal batch cultures. *J. Anim. Sci.* 85: 2556–2563.

USDA (US Department of Agriculture). 2000. Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States (R.L. Kellogg, C.H. Lander, D.C. Moffitt, and N. Gollehon, eds.). Washington, DC, US Department of Agriculture.

USDA (US Department of Agriculture). 2007. Dairy 2007, Part I: Reference of Dairy Cattle Health and Management Practices in the United States. Fort Collins, CO.

Ushida, K. 2010. Symbiotic methanogens and rumen ciliates. *In* J.H.P. Hackstein, ed. *(Endo) symbiotic Methanogenic Archaea*, pp. 25–34. Heidelberg, Springer-Verlag.

Uwituze, S., Parsons, G.L., Schneider, C.J., Karges, K.K., Gibson, M.L., Hollis, L.C., Higgins, J.J. & Drouillard, J.S. 2011. Evaluation of sulphur content of dried distillers grains with solubles in finishing diets based on steam-flaked corn or dry-rolled corn. *J. Anim. Sci.* 89: 2582–2591.

Vallejo, A., Skiba, U.M., Garcia-Torres, L., Arce, A., Lopez-Fernandez, S. & Sanchez-Martin, L. 2006. Nitrogen oxides emission from soils bearing a potato crop as influenced by fertilization with treated pig slurries and composts. *Soil Biol. Biochem.* 38: 2782–2793.

Van Amburgh, M.E., Galton, D.M., Bauman, D.E. & Everett, R.W. 1997. Management and economics of extended calving intervals with use of bovine somatotropin. *Livest. Prod. Sci.* 50: 15–28.

Van der Stelt, B., van Vliet, P.C., Reijs, J.W., Temminghoff, E.J. & van Riemsdijk, W.H. 2008. Effects of dietary protein and energy levels on cow manure excretion and ammonia volatilization. *J. Dairy Sci.* 91: 4811–4821.

van Groenigen, J.W., Kasper, G.J., Velthof, G.L., van den Pol van Dasselaar, A. & Kuikman, P.J. 2004. Nitrous oxide emissions from silage maize fields under different mineral nitrogen fertilizer and slurry applications. *Plant Soil* 263: 101–111.

Van Soest, P.J. 1994. *Nutritional Ecology of the Ruminant*. Ithaca, N.Y., Cornell University Press.

Van Vugt, S.J., Waghorn, G.C., Clark, D.A. & Woodward, S.L. 2005. Impact of monensin on methane production and performance of cows fed forage diets. *Proc. N. Z. Soc. Anim. Prod.* 65: 362–366.

Van Vuuren, A.M. 2003. Effect of live yeast on the performance of dairy cows. *In* A.M. van Vuuren, ed. *The Role of Probiotics in Animal Nutrition and Their Link to the Demands of European Consumers*. The Netherlands, TNO Publications.

Van Zijderveld, S.M., Gerrits, W.J.J., Apajalahti, J.A., Newbold, J.R., Dijkstra, J., Leng, R.A. & Perdok, H.B. 2010. Nitrate and sulfate: Effective alternative hydrogen sinks for mitigation of ruminal methane production in sheep. *J. Dairy Sci.* 93: 5856–5866.

Van Zijderveld, S.M., Fonken, B., Dijkstra, J., Gerrits, W.J.J., Perdok, H.B., Fokkink, W. and Newbold, J.R. 2011a. Effects of a combination of feed additives on methane production, diet digestibility, and animal performance in lactating dairy cows. *J. Dairy Sci.* 94: 1145–1454.

Van Zijderveld, S.M., Gerrits, W.J.J., Dijkstra, J., Newbold, J.R., Hulshof, R.B.A. & Perdok, H.B. 2011b. Persistency of methane mitigation by dietary nitrate supplementation in dairy cows. *J. Dairy Sci.* 94: 4028–4038.

Van Zijderveld, S.M., Dijkstra, J., Perdok, H.B., Newbold, J.R. & Gerrits, W.J.J. 2011c. Dietary inclusion of diallyl disulfide, yucca powder, calcium fumarate, an extruded linseed product, or medium-chain fatty acids does not affect methane production in lactating dairy cows. *J. Dairy Sci.* 94: 3094–3104.

Vander Pol, M., Hristov, A.N., Zaman, S. & Delano, N. 2008. Peas can replace soybean meal and corn grain in dairy cow diets. *J. Dairy Sci.* 91: 698–703.

VanderZaag, A.C., Gordon, R., Glass, V. & Jamieson, R. 2008. Floating Covers to Reduce Gas Emissions from Liquid Manure Storages: a Review. *Appl. Eng. Agric.* 24: 657–671.

VanderZaag, A.C., Gordon, R., Jamieson, R., Burton, D. & Stratton, G. 2009 Gas emissions from straw covered liquid dairy manure during summer storage and autumn agitation. *Transactions of the ASABE* 52: 599–608.

VanderZaag, A.C., Gordon, R., Jamieson, R., Burton, D. & Stratton, G. 2010. Permeable synthetic covers for controlling emissions from liquid dairy manure. *Appl. Eng. Agric.* 26: 287–297.

VanderZaag, A.C., Jayasundara, S. & Wagner-Riddle, C. 2011. Strategies to mitigate nitrous oxide emissions from land applied manure. *Anim. Feed Sci. Technol.* 166–167: 464–479.

Van Dorland, H.A., Kreuzer, M., Leuenberger, H. & Wettstein, H.-R. 2008. Comparative potential of white and red clover to modify the milk fatty acid profile of cows fed ryegrass-based diets from zero-grazing and silage systems. *J. Sci. Food Agric.* 88: 77–85.

Van Middelaar, C.E., Berentsen, P.B.M., Dijkstra, J. & De Boer, I.J.M. 2012. Evaluation of a feeding strategy to reduce greenhouse gas emissions from milk production: The level of analysis matters. *J. Anim. Sci. 90* (Suppl. 3): 707.

Vanotti, M.B., Szogi, A.A. & Vives, C.A. 2008. Greenhouse gas emission reduction and environmental quality improvement from implementation of aerobic waste treatment systems in swine farms. *Waste Manage.* 28: 759–766.

VanRaden, P.M., Tooker, M.E., Cole, J.B., Wiggans, G.R. & Megonigal, J.H. Jr. 2007. Genetic Evaluations for mixed-breed populations. *J. Dairy Sci.* 90: 2434–2441.

Varel, V.H., Nienaber, J.A. & Freetly, H.C. 1999. Conservation of nitrogen in cattle feedlot waste with urease inhibitors. *J. Anim. Sci.* 77: 1162–1168.

Varel, V.H. & Wells, J.E. 2007. Influence of thymol and a urease inhibitor on coliform bacteria, odor, urea, and methane from a swine production manure pit. *J. Environ. Qual.* 36: 773–779.

Vellinga, T.V. & Hoving, I.E. 2011. Maize silage for dairy cows: mitigation of methane emissions can be offset by land use change. *Nutr. Cycl. Agroecosyst.* 89: 413–426.

Velthof, G.L. & Mosquera, J. 2011. The impact of slurry application technique on nitrous oxide emission from agricultural soils. *Agric. Ecosyst. Environ.* 140: 298–308.

Velthof, G.L., Kuikman, P.J. & Oenema, O. 2003. Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biol. Fertil. Soils* 37: 221–230.

Velthof, G.L., Nelemans, J.A., Oenema, O. & Kuikman, P.J. 2005. Gaseous nitrogen and carbon losses from pig manure derived from different diets. *J. Environ. Qual.* 34: 698–706.

Velthof, G.L., Oudendag, D., Witzke, H.P., Asman, W.A.H., Klimont, Z. & Oenema, O. 2009. Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. *J. Environ. Qual.* 38: 402–417.

Verdier, J., Zhao, J., Torres-Jerez, I., Ge, S., Liu, C., He, X., Mysore, K.S., Dixon, R.A. & Udvardi, M.K. 2012. MtPAR MYB transcription factor acts as an on switch for proanthocyanidin biosynthesis in Medicago truncatula. *Proc. Nat. Acad. Sci. USA.* 109: 766–1771.

Vermeulen, J., Huysmans, A., Crespo, M., Van Lierde, S., De Rycke, A. & Verstraete, A. 1992. *In* Processing of biowaste by anaerobic composting to plant growth substrates, pp. 147–157. Proceedings of the International Symposium on Anaerobic Digestion of Solid Waste, Venice.

VIsalvethaya, W., Tanasuparuk, W. & Techakumphu, M. 2011. The development of a model for artificial insemination by backyard pig farmers in Thailand. *Trop. Anim. Health Prod.* 43: 787–793

Voelker Linton, J.A. & Allen, M.S. 2009. Nutrient demand interacts with forage family to affect nitrogen digestion and utilization responses in dairy cows. *J. Dairy Sci.* 92: 1594–1602.

Voermans, J.A.M. & Hendriks, J.G.L. 1995. Pit or roof ventilation for growing finishing pigs. Research Institute for Pig Husbandry, Rosmalen, The Netherlands. Proefverslag nummer pp. 4–9.

Vogels, G.D., Hoppe, W.F. & Stumm, C,K. 1980. Association of methanogenic bacteria with rumen ciliates. *Appl. Environ. Microbiol.* 40: 608–612.

von Uexküll, H.R. & Mutert, E. 1995. Global extent, development and economic impact of acid soils. *Plant and Soil* 171: 1–15.

Waghorn, G.C. 2008. Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production – progress and challenges. *Anim. Feed Sci. Technol.* 147: 116–139.

Waghorn, G.C. & Jones, W.T. 1989. Bloat in cattle 46. The potential of Dock (*Rumex obtusifolius*) as an antibloat agent for cattle. *N. Z. J. Agric. Res.* 32: 227–235.

Waghorn, G.C. & Hegarty, R.S. 2011. Lowering ruminant methane emissions through improved feed conversion efficiency. *Anim. Feed Sci. Technol.* 166–167: 291–301.

Waghorn, G.C., Tavendale, M.H. & Woodfield, D.R. 2002. Mathanogenesis from forages fed to sheep. *Proc. N. Z. Grassland Assoc.* 64: 167–171.

Waghorn, G.C., Woodward, S.L., Tavendale, M. & Clark, D.A. 2006. Inconsistencies in rumen methane production – effects of forage composition and animal genotype. *Int. Congr. Series* 1293: 115–118.

Waghorn, G.C., Clark, H., Taufa, V. & Cavanagh, A. 2008. Monensin controlled-release capsules for methane mitigation in pasture-fed dairy cows. *Aust. J. Exp. Agr.* 48: 65–68.

Wagner-Riddle, C. and Thurtell, G.W. 1998. Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. *Nutr. Cycling Agroecosyst.* 52: 151–163.

Wall, E., Simm, G. & Moran, D. 2010. Developing breeding schemes to assist mitigation of greenhouse gas emissions. *Animal* 4: 366–376.

Wallace, R.J., McEwan, N.R., McIntosh, F.M., Teferedegne, B. & Newbold, C.J. 2002. Natural products as manipulators of rumen fermentation. *Asian-Aust. J. Anim. Sci.* 15: 1458–1468.

Wallace, R.J., McKain, N., Shingfield, K.J. & Devillard, E. 2007. Isomers of conjugated linoleic acids are synthesized via different mechanisms in ruminal digesta and bacteria. *J. Lipid Res.* 48: 2247–2254.

Walli, T.K. 2011. Biological treatment of straws. *In* Successes and failures with animal nutrition practices and technologies in developing countries, pp. 57–61. Proceedings of the FAO electronic conference, 1-30 September 2010, Rome, Italy.

Wang, C.J., Wang, S.P. & Zhouc, H. 2009. Influences of flavomycin, ropadiar, and saponin on nutrient digestibility, rumen fermentation, and methane emission from sheep. *Anim. Feed Sci. Technol.* 148: 157–166.

Wang, J., Ye, J. & Liu, J. 2012. Effects of tea saponins on rumen microbiota, rumen fermentation, methane production and growth performance – a review. *Trop. Anim. Health Prod.* 44: 697–706.

Ward, A.J., Hobbs, P.J., Holliman, P.J. & Jones, D.L. 2008. Optimisation of the anaerobic digestion of agricultural resources. *Bioresource Technol.* 99: 7928–7940.

Warnick, L.D., Janssen, D., Guard, C.L. & Gröhn, Y.T. 2001. The effect of lameness on milk production in dairy cows. *J. Dairy Sci.* 84: 1988–1997.

Wattiaux, M.A. & Karg, K.L. 2004. Protein level for alfalfa and corn silage based diets. II. Nitrogen balance and manure characteristics. *J. Dairy Sci.* 87: 3492–3502.

Wedlock, D.N., Pedersen, G., Denis, M., Dey, D., Janssen, P.H. & Buddle, B.M. 2010. Development of a vaccine to mitigate greenhouse gas emissions in agriculture; vaccination of sheep with methanogen fractions induces antibodies that block methane production in vitro. *N. Z. Vet. J.* 58: 29–36.

Weigel, K.A. 2004. Exploring the role of sexed semen in dairy production systems. *J. Dairy Sci.* 87: (E. Suppl.): E120–E130.

Weigel, K.A. 2006. Prospects for improving reproductive performance through genetic selection. *Anim. Reprod. Sci.* 96: 323–330.

Weinberg, Z.G. & Muck, R.E. 1996. New trends and opportunities in the development and use of inoculants for silage. *FEMS Microbiol. Rev.* 19: 53–68.

Weinberg, Z.G., Muck, R.E. & Weimer, P.J. 2003. The survival of silage inoculant lactic acid bacteria in rumen fluid. *J. Appl. Microbiol.* 94: 1066–1071.

Weiss, W.P & Wyatt, D.J. 2000. Effect of oil content and kernel processing of corn silage on digestibility and milk production by dairy cows. *J. Dairy Sci.* 83: 351–358.

Weiss, W.P. & Wyatt, D.J. 2006. Effect of corn silage hybrid and metabolizable protein supply on nitrogen metabolism of dairy cows. *J. Dairy Sci.* 89: 1644–1653.

Weiss, W.P. & Pinos-Rodriguez, J.M. 2009. Production responses of dairy cows when fed supplemental fat in low- and high-forage diets. *J. Dairy Sci.* 92: 6144–6155.

Weiss, W.P., St-Pierre, N.R. & Willett, L.B. 2009a. Varying type of forage, concentration of metabolizable protein, and source of carbohydrate affects nutrient digestibility and production by dairy cows. *J. Dairy Sci.* 92: 5595–5606.

Weiss, W.P., Willett, L.B., St-Pierre, N.R., Borger, D.C., McKelvey, T.R. & Wyatt, D.J. 2009b. Varying forage type, metabolizable protein concentration, and carbohydrate source affects manure excretion, manure ammonia, and nitrogen metabolism of dairy cows. *J. Dairy Sci.* 92: 5607–5619.

Whitlock, L.A., Schingoethe, D.J., Hippen, A.R., Kalscheur, K.F. & AbuGhazaleh, A.A. 2003. Milk production and composition from cows fed high oilor conventional corn at two forage concentrations. *J. Dairy Sci.* 86: 2428–2437.

Williams, Y.J., Popovski, S., Rea, S.M., Skillman, L.C., Toovey, A.F., Northwood, K.S. & Wright, A.D.G. 2009. A vaccine against rumen methanogens can alter the composition of archaeal populations. *Appl. Environ. Microbiol.* 75: 1860–1866.

Williams, S.R.O., Moate, P.J., Hannah, M.C., Ribaux, B.E., Wales, W.J. & Eckard, R.J. 2011. Background matters with the SF_6 tracer method for estimating enteric methane emissions from dairy cows: A critical evaluation of the SF_6 procedure. *Anim. Feed Sci. Technol.* 170: 265–276.

Wilson, D.J., Gonzalez, R.N. & Das, H.H. 1997. Bovine mastitis pathogens in New York and Pennsylvania: prevalence and effects on somatic cell count and milk production. *J. Dairy Sci.* 80: 2592–2598.

Winichayakul, S., Cookson, R., Scott, R., Zhou, J., Zou, X., Roldan, M., Richardson, K. & Roberts, N. 2008. Delivery of grasses with high levels of unsaturated, protected fatty acids. *Proc. NZ Grassld. Assoc.* 70: 211–216.

Witter, E., Martensson, A.M. & Garvia, F.V. 1993. Size of the soil microbial biomass in a long-term field experiment as affected by different N-fertilizers and organic manures. *Soil Biol. Biochem.* 25: 659–669.

Wolf, B., Zheng, X., Brüggemann, N., Chen, W., Dannenmann, M., Han, X., Sutton, M.A., Wu, H., Yao, Z. & Butterbach-Bahl, K. 2010. Grazing-induced reduction of natural nitrous oxide release from continental steppe. *Nature* 464: 881–884.

Wolfe, R.S. 1979. Microbial biochemistry of methane – A study in contrasts. *Micr.Biochem.* 21: 335.

Wolin, M.J. 1960. A theoretical rumen fermentation balance. *J. Dairy Sci.* 40: 1452–1459.

Wood, T.A., Wallace, R.J., Rowe, A., Price, J., Yáñez-Ruiz, D.R., Murray, P. & Newbold, C.J. 2009. Encapsulated fumaric acid as a feed ingredient to decrease ruminal methane emissions. *Anim. Feed Sci. Technol.* 152: 62–71.

Woodward, S.L., Waghorn, G.C., Ulyatt, M.J. & Lassey, K.R. 2001. Early indications that feeding Lotus will reduce methane emissions from ruminants. *Proc. N. Z. Soc. Anim. Prod.* 61: 23–26.

Woodward, S.L., Waghorn, G.C & Thomson, N.A. 2006. Supplementing dairy cows with oils to improve performance and reduce methane – does it work? *Proc. N. Z. Soc. Anim. Prod.* 66: 176–181.

Wright, A.D.G., Kennedy, P., O'Neill, C.J., Toovey, A.F., Popovski, S., Rea, S.M., Pimma, C.L. & Klein, L. 2004. Reducing methane emissions in sheep by immunization against rumen methanogens. *Vaccine* 22: 3976–3985.

Wright, A.D.G. & Klieve, A.V. 2011. Does the complexity of the rumen microbial ecology preclude methane mitigation? *Anim. Feed Sci. Technol.* 166–167: 248–253.

Wu, Z. & Satter, L.D. 2000. Milk production during the complete lactation of dairy cows fed diets containing different amounts of protein. *J. Dairy Sci.* 83: 1042–1051.

Wu-Haan, W., Powers, W.J., Angel, C.R., Hale, C.E. & Applegate, T.J. 2007. Effect of an acidifying diet combined with zeolite and slight protein reduction on air emissions from laying hens of different ages. *Poultry Sci.* 86: 182–190.

Yan, T., Agnew, R.E., Gordon, F.J. & Porter, M.G. 2000. Prediction of methane energy output in dairy and beef cattle offered grass silage-based diets. *Livest. Prod. Sci.* 64: 253–263.

Yáñez-Ruiz, D.R., Macias, B., Pinloche, E. & Newbold, C.J. 2010. The persistence of bacterial and methanogenic archaeal communities residing in the rumen of young lambs. *FEMS Microbiol. Ecol.* 72: 272–278.

Yang, S.L., Bu, D.P., Wang, J.Q., Hu, Z.Y., Li, D., Wei, H.W., Zhou, L.Y. & Loor, J.J. 2009. Soybean oil and linseed oil affect profiles of ruminal microorganisms in dairy cows. *Animal* 3: 1562–1569.

Yang, W.Z. & Beauchemin, K.A. 2009. Increasing physically effective fibre content of dairy cow diets through forage proportion versus forage chop length: Chewing and ruminal pH. *J. Dairy Sci.* 92: 1603–1615.

Yang, W.Z., Oba, M. & McAllister, T.A. 2012. Precision processing maximizes the feed value of barley grain for feedlot cattle. *Prairie Post Bull Breeders*, February 2012: A12–13.

Yen, J.T. & Veum, T.L. 1982. Effect of lysine, tryptophan and(or) carbadox additions to low protein corn-soybean meal diets for young pigs. *J. Anim. Sci.* 55: 1099–1108.

Yurtseven, S. & Ozturk, I. 2009. Influence of two sources of cereals (corn or barley), in free choice feeding on diet selection, milk production indices and gaseous products in lactating sheep. *Asian J. Anim. Vet. Adv.* 4: 76–85.

Yurtseven, S., Cetin, M., Ozturk, I., Can, A., Boga, M., Sahin, T. & Turkoglu, H. 2009. Effect of different feeding method on methane and carbon dioxide emissions milk yield and composition of lactating awassi sheep. *Asian J. Anim. Vet. Adv.* 4: 278–287.

Zaman, M. and Blennerhassett, J.D. 2010. Effects of the different rates of urease and nitrification inhibitors on gaseous emissions of ammonia and nitrous oxide, nitrate leaching and pasture production from urine patches in an intensive grazed pasture system. *Agric. Ecosyst. Environ.* 136: 236–246.

Zhang, J., Feng, F., Chen, X. & Li, Q. 2012. Degrading mimosine and tannins of *Leucaena leucocephala* by ensiling. *In* K. Kuoppala, M. Rinne and A. Vanhatalo, eds. Proc. of the XVI Int. Silage Conf. Hameenlinna, Finland, pp. 254–255. University of Helsinki , MTT Agrifood Research Finland.

Zebeli, Q., Mansmann, D., Steingass, H. & Ametaj, B.N. 2010. Balancing diets for physically effective fibre and ruminally degradable starch: A key to lower the risk of sub-acute rumen acidosis and improve productivity of dairy cattle. *Livest. Sci.* 127:1–10.

Zeeman, G. 1994. Methane Production/emission in Storages for Animal Manure. *Fert. Res.* 37: 207–211.

Zeman, C., Depken, D. & Rich, M. 2002. Research on how the composting process impacts greenhouse gas emissions and global warming. *Compost Sci. Utiliz.* 10: 72–86.

Zemmelink, G., Ifar, S. & Oosting, S.J. 2003. Optimum utilization of feed resources: model studies and farmers' practices in two villages in East Java, Indonesia. *Agric. Syst.* 76: 77–94.

Zhou, Y.Y., Mao, H.L., Jiang, F., Wang, J.K., Liu, J.X. & McSweeney, C.S. 2011a. Inhibition of rumen methanogenesis by tea saponins with reference to fermentation pattern and microbial communities in Hu sheep. *Anim. Feed Sci. Technol.* 166–167: 93–100.

Zhou, M., Chung, Y.-H., Beauchemin, K.A., Holtshausen, L., Oba, M., McAllister, T.A. & Guan, L.L. 2011b. Relationship between rumen methanogens and methane production in dairy cows fed diets supplemented with feed enzyme addition. *J. Appl. Microbiol.* 111: 1148–1158.

Zi, X.-D. 2003. Reproduction in female yaks (Bos grunniens) and opportunities for improvement. *Theriogenology* 59: 1302–1312.

Ziekus, J.G. 1977. The biology of methanogenic bacteria. *Bacteriol. Rev.* 4: 514–541.

FAO TECHNICAL PAPERS

FAO ANIMAL PRODUCTION AND HEALTH PAPERS

1 Animal breeding: selected articles from the *World Animal Review*, 1977 (C E F S)
2 Eradication of hog cholera and African swine fever, 1976 (E F S)
3 Insecticides and application equipment for tsetse control, 1977 (E F)
4 New feed resources, 1977 (E/F/S)
5 Bibliography of the criollo cattle of the Americas, 1977 (E/S)
6 Mediterranean cattle and sheep in crossbreeding, 1977 (E F)
7 The environmental impact of tsetse control operations, 1977 (E F)
7 Rev.1 The environmental impact of tsetse control operations, 1980 (E F)
8 Declining breeds of Mediterranean sheep, 1978 (E F)
9 Slaughterhouse and slaughterslab design and construction, 1978 (E F S)
10 Treating straw for animal feeding, 1978 (C E F S)
11 Packaging, storage and distribution of processed milk, 1978 (E)
12 Ruminant nutrition: selected articles from the *World Animal Review*, 1978 (C E F S)
13 Buffalo reproduction and artificial insemination, 1979 (E*)
14 The African trypanosomiases, 1979 (E F)
15 Establishment of dairy training centres, 1979 (E)
16 Open yard housing for young cattle, 1981 (Ar E F S)
17 Prolific tropical sheep, 1980 (E F S)
18 Feed from animal wastes: state of knowledge, 1980 (C E)
19 East Coast fever and related tick-borne diseases, 1980 (E)
20/1 Trypanotolerant livestock in West and Central Africa – Vol. 1. General study, 1980 (E F)
20/2 Trypanotolerant livestock in West and Central Africa – Vol. 2. Country studies, 1980 (E F)
20/3 Le bétail trypanotolérant en Afrique occidentale et centrale – Vol. 3. Bilan d'une décennie, 1988 (F)
21 Guideline for dairy accounting, 1980 (E)
22 Recursos genéticos animales en América Latina, 1981 (S)
23 Disease control in semen and embryos, 1981 (C E F S)
24 Animal genetic resources – conservation and management, 1981 (C E)
25 Reproductive efficiency in cattle, 1982 (C E F S)
26 Camels and camel milk, 1982 (E)
27 Deer farming, 1982 (E)
28 Feed from animal wastes: feeding manual, 1982 (C E)
29 Echinococcosis/hydatidosis surveillance, prevention and control: FAO/UNEP/WHO guidelines, 1982 (E)
30 Sheep and goat breeds of India, 1982 (E)
31 Hormones in animal production, 1982 (E)
32 Crop residues and agro-industrial by-products in animal feeding, 1982 (E/F)
33 Haemorrhagic septicaemia, 1982 (E F)
34 Breeding plans for ruminant livestock in the tropics, 1982 (E F S)
35 Off-tastes in raw and reconstituted milk, 1983 (Ar E F S)
36 Ticks and tick-borne diseases: selected articles from the *World Animal Review*, 1983 (E F S)
37 African animal trypanosomiasis: selected articles from the *World Animal Review*, 1983 (E F)
38 Diagnosis and vaccination for the control of brucellosis in the Near East, 1982 (Ar E)
39 Solar energy in small-scale milk collection and processing, 1983 (E F)
40 Intensive sheep production in the Near East, 1983 (Ar E)
41 Integrating crops and livestock in West Africa, 1983 (E F)
42 Animal energy in agriculture in Africa and Asia, 1984 (E/F S)

43 Olive by-products for animal feed, 1985 (Ar E F S)
44/1 Animal genetic resources conservation by management, data banks and training, 1984 (E)
44/2 Animal genetic resources: cryogenic storage of germplasm and molecular engineering, 1984 (E)
45 Maintenance systems for the dairy plant, 1984 (E)
46 Livestock breeds of China, 1984 (E F S)
47 Réfrigération du lait à la ferme et organisation des transports, 1985 (F)
48 La fromagerie et les variétés de fromages du bassin méditerranéen, 1985 (F)
49 Manual for the slaughter of small ruminants in developing countries, 1985 (E)
50 Better utilization of crop residues and by-products in animal feeding: research guidelines – 1. State of knowledge, 1985 (E)
50/2 Better utilization of crop residues and by-products in animal feeding: research guidelines – 2. A practical manual for research workers, 1986 (E)
51 Dried salted meats: charque and carne-de-sol, 1985 (E)
52 Small-scale sausage production, 1985 (E)
53 Slaughterhouse cleaning and sanitation, 1985 (E)
54 Small ruminants in the Near East – Vol. I. Selected papers presented for the Expert Consultation on Small Ruminant Research and Development in the Near East (Tunis, 1985), 1987 (E)
55 Small ruminants in the Near East – Vol. II. Selected articles from *World Animal Review* 1972-1986, 1987 (Ar E)
56 Sheep and goats in Pakistan, 1985 (E)
57 The Awassi sheep with special reference to the improved dairy type, 1985 (E)
58 Small ruminant production in the developing countries, 1986 (E)
59/1 Animal genetic resources data banks – 1. Computer systems study for regional data banks, 1986 (E)
59/2 Animal genetic resources data banks – 2. Descriptor lists for cattle, buffalo, pigs, sheep and goats, 1986 (E F S)
59/3 Animal genetic resources data banks – 3. Descriptor lists for poultry, 1986 (E F S)
60 Sheep and goats in Turkey, 1986 (E)
61 The Przewalski horse and restoration to its natural habitat in Mongolia, 1986 (E)
62 Milk and dairy products: production and processing costs, 1988 (E F S)
63 Proceedings of the FAO expert consultation on the substitution of imported concentrate feeds in animal production systems in developing countries, 1987 (C E)
64 Poultry management and diseases in the Near East, 1987 (Ar)
65 Animal genetic resources of the USSR, 1989 (E)
66 Animal genetic resources – strategies for improved use and conservation, 1987 (E)
67/1 Trypanotolerant cattle and livestock development in West and Central Africa – Vol. I, 1987 (E)
67/2 Trypanotolerant cattle and livestock development in West and Central Africa – Vol. II, 1987 (E)
68 Crossbreeding *Bos indicus* and *Bos taurus* for milk production in the tropics, 1987 (E)
69 Village milk processing, 1988 (E F S)
70 Sheep and goat meat production in the humid tropics of West Africa, 1989 (E/F)
71 The development of village-based sheep production in West Africa, 1988 (Ar E F S) (Published as Training manual for extension workers, M/S5840E)
72 Sugarcane as feed, 1988 (E/S)
73 Standard design for small-scale modular slaughterhouses, 1988 (E)
74 Small ruminants in the Near East – Vol. III. North Africa, 1989 (E)
75 The eradication of ticks, 1989 (E/S)
76 Ex situ cryoconservation of genomes and genes of endangered cattle breeds by means of modern biotechnological methods, 1989 (E)

77 Training manual for embryo transfer in cattle, 1991 (E)
78 Milking, milk production hygiene and udder health, 1989 (E)
79 Manual of simple methods of meat preservation, 1990 (E)
80 Animal genetic resources – a global programme for sustainable development, 1990 (E)
81 Veterinary diagnostic bacteriology – a manual of laboratory procedures of selected diseases of livestock, 1990 (E F)
82 Reproduction in camels – a review, 1990 (E)
83 Training manual on artificial insemination in sheep and goats, 1991 (E F)
84 Training manual for embryo transfer in water buffaloes, 1991 (E)
85 The technology of traditional milk products in developing countries, 1990 (E)
86 Feeding dairy cows in the tropics, 1991 (E)
87 Manual for the production of anthrax and blackleg vaccines, 1991 (E F)
88 Small ruminant production and the small ruminant genetic resource in tropical Africa, 1991 (E)
89 Manual for the production of Marek's disease, Gumboro disease and inactivated Newcastle disease vaccines, 1991 (E F)
90 Application of biotechnology to nutrition of animals in developing countries, 1991 (E F)
91 Guidelines for slaughtering, meat cutting and further processing, 1991 (E F)
92 Manual on meat cold store operation and management, 1991 (E S)
93 Utilization of renewable energy sources and energy-saving technologies by small-scale milk plants and collection centres, 1992 (E)
94 Proceedings of the FAO expert consultation on the genetic aspects of trypanotolerance, 1992 (E)
95 Roots, tubers, plantains and bananas in animal feeding, 1992 (E)
96 Distribution and impact of helminth diseases of livestock in developing countries, 1992 (E)
97 Construction and operation of medium-sized abattoirs in developing countries, 1992 (E)
98 Small-scale poultry processing, 1992 (Ar E)
99 In situ conservation of livestock and poultry, 1992 (E)
100 Programme for the control of African animal trypanosomiasis and related development, 1992 (E)
101 Genetic improvement of hair sheep in the tropics, 1992 (E)
102 Legume trees and other fodder trees as protein sources for livestock, 1992 (E)
103 Improving sheep reproduction in the Near East, 1992 (Ar)
104 The management of global animal genetic resources, 1992 (E)
105 Sustainable livestock production in the mountain agro-ecosystem of Nepal, 1992 (E)
106 Sustainable animal production from small farm systems in South-East Asia, 1993 (E)
107 Strategies for sustainable animal agriculture in developing countries, 1993 (E F)
108 Evaluation of breeds and crosses of domestic animals, 1993 (E)
109 Bovine spongiform encephalopathy, 1993 (Ar E)
110 L'amélioration génétique des bovins en Afrique de l'Ouest, 1993 (F)
111 L'utilización sostenible de hembras F1 en la producción del ganado lechero tropical, 1993 (S)
112 Physiologie de la reproduction des bovins trypanotolérants, 1993 (F)
113 The technology of making cheese from camel milk (*Camelus dromedarius*), 2001 (E F)
114 Food losses due to non-infectious and production diseases in developing countries, 1993 (E)
115 Manuel de formation pratique pour la transplantation embryonnaire chez la brebis et la chèvre, 1993 (F S)
116 Quality control of veterinary vaccines in developing countries, 1993 (E)
117 L'hygiène dans l'industrie alimentaire, 1993 – Les produits et l'aplication de l'hygiène, 1993 (F)
118 Quality control testing of rinderpest cell culture vaccine, 1994 (E)
119 Manual on meat inspection for developing countries, 1994 (E)

120 Manual para la instalación del pequeño matadero modular de la FAO, 1994 (S)
121 A systematic approach to tsetse and trypanosomiasis control, 1994 (E/F)
122 El capibara (*Hydrochoerus hydrochaeris*) – Estado actual de su producción, 1994 (S)
123 Edible by-products of slaughter animals, 1995 (E S)
124 L’approvisionnement des villes africaines en lait et produits laitiers, 1995 (F)
125 Veterinary education, 1995 (E)
126 Tropical animal feeding – A manual for research workers, 1995 (E)
127 World livestock production systems – Current status, issues and trends, 1996 (E)
128 Quality control testing of contagious bovine pleuropneumonia live attenuated vaccine – Standard operating procedures, 1996 (E F)
129 The world without rinderpest, 1996 (E)
130 Manual de prácticas de manejo de alpacas y llamas, 1996 (S)
131 Les perspectives de développement de la filière lait de chèvre dans le bassin méditerranéen, 1996 (F)
132 Feeding pigs in the tropics, 1997 (E)
133 Prevention and control of transboundary animal diseases, 1997 (E)
134 Tratamiento y utilización de residuos de origen animal, pesquero y alimenticio en la alimentación animal, 1997 (S)
135 Roughage utilization in warm climates, 1997 (E F)
136 Proceedings of the first Internet Conference on Salivarian Trypanosomes, 1997 (E)
137 Developing national emergency prevention systems for transboundary animal diseases, 1997 (E)
138 Producción de cuyes (*Cavia porcellus*), 1997 (S)
139 Tree foliage in ruminant nutrition, 1997 (E)
140/1 Analisis de sistemas de producción animal – Tomo 1: Las bases conceptuales, 1997 (S)
140/2 Analisis de sistemas de producción animal – Tomo 2: Las herramientas basicas, 1997 (S)
141 Biological control of gastro-intestinal nematodes of ruminants using predacious fungi, 1998 (E)
142 Village chicken production systems in rural Africa – Household food security and gender issues, 1998 (E)
143 Agroforestería para la producción animal en América Latina, 1999 (S)
144 Ostrich production systems, 1999 (E)
145 New technologies in the fight against transboundary animal diseases, 1999 (E)
146 El burro como animal de trabajo – Manual de capacitación, 2000 (S)
147 Mulberry for animal production, 2001 (E)
148 Los cerdos locales en los sistemas tradicionales de producción, 2001 (S)
149 Animal production based on crop residues – Chinese experiences, 2001 (C E)
150 Pastoralism in the new millennium, 2001 (E)
151 Livestock keeping in urban areas – A review of traditional technologies based on literature and field experiences, 2001 (E)
152 Mixed crop-livestock farming – A review of traditional technologies based on literature and field experiences, 2001 (E)
153 Improved animal health for poverty reduction and sustainable livelihoods, 2002 (E)
154 Goose production, 2002 (E F)
155 Agroforestería para la producción animal en América Latina – II, 2003 (S)
156 Guidelines for coordinated human and animal brucellosis surveillance, 2003 (E)
157 Resistencia a los antiparasitarios – Estado actual con énfasis en América Latina, 2003 (S)
158 Employment generation through small-scale dairy marketing and processing, 2003 (E)
159 Good practices in planning and management of integrated commercial poultry production in South Asia, 2003 (E)
160 Assessing quality and safety of animal feeds, 2004 (E, C)
161 FAO technology review: Newcastle disease, 2004 (E)

162 Uso de antimicrobianos en animales de consumo – Incidencia del desarrollo de resistencias en la salud pública, 2004 (S)
163 HIV infections and zoonoses, 2004 (E F S)
164 Feed supplementation blocks – Urea-molasses multinutrient blocks: simple and effective feed supplement technology for ruminant agriculture, 2007 (E)
165 Biosecurity for Highly Pathogenic Avian Influenza – Issues and options, 2008 (E F Ar V)
166 International trade in wild birds, and related bird movements, in Latin America and the Caribbean, 2009 (S^e E^e)
167 Livestock keepers – guardians of biodiversity, 2009 (E)
168 Adding value to livestock diversity – Marketing to promote local breeds and improve livelihoods, 2010 (E, F, S)
169 Good practices for biosecurity in the pig sector – Issues and options in developing and transition countries, 2010 (E, F, C, R** S**)
170 La salud pública veterinaria en situaciones de desastres naturales y provocados, 2010 (S)
171 Approaches to controlling, preventing and eliminating H5N1 HPAI in endemic countries, 2011 (E)
172 Crop residue based densified total mixed ration – A user-friendly approach to utilise food crop by-products for ruminant production, 2012 (E)
173 Balanced feeding for improving livestock productivity – Increase in milk production and nutrient use efficiency and decrease in methane emission, 2012 (E)
174 Invisible Guardians - Women manage livestock diversity, 2012 (E)
175 Enhancing animal welfare and farmer income through strategic animal feeding - Some case studies, 2013 (E)
176 Lessons from HPAI – A technical stocktaking of coutputs, outcomes, best practices and lessons learned from the fight against highly pathogenic avian influenza in Asia 2005–2011, 2013 (E)
177 Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO_2 emissions, 2013 (E)

Availability: June 2013

Ar – Arabic
C – Chinese
E – English
F – French
P – Portuguese
S – Spanish
R – Russian
V – Vietnamese

Multil – Multilingual
* Out of print
** In preparation
^{e} E-publication

The *FAO Technical Papers* are available through the authorized FAO Sales Agents or directly from Sales and Marketing Group, FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy.

Find more publications at
http://www.fao.org/ag/againfo/resources/en/publications.html

Animal agriculture substantially contributes to the world economy by providing food, jobs, and financial security for billions of people. With increasing concerns over global climate change and pollution, efforts are underway to reduce the overall environmental impact of animal production. This document analyses emission of non-carbon dioxide greenhouse gases, an important segment of the environmental footprint of animal production. It has been developed by a team that included experts in animal/ruminant nutrition, manure and soil management, animal and whole-farm modeling, and animal reproduction. Over 900 publications focusing on nutritional and manure management mitigation strategies for methane (enteric or from manure) and nitrous oxide emissions were reviewed and analysed, and a synthesis of feed-, animal management- and manure management-based mitigation approaches and interactions amongst them has been presented. This document will help researchers, animal industry consultants, policy-makers, animal producers, non-governmental organizations, and other groups with interest in maintaining a viable and environmentally-responsible animal production sector to make sound decisions on selection and adoption of effective and economically feasible greenhouse gas mitigation practices.

ISBN 978-92-5-107658-3 ISSN 0254-6019

9 789251 076583

I3288E/1/04.13