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SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options[1]

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ABSTRACT: The goal of this review was to analyze published data on animal management practices that mitigate enteric methane (CH_4) and nitrous oxide (N_2O) emissions from animal operations. Increasing animal productivity can be a very effective strategy for reducing greenhouse gas (GHG) emissions per unit of livestock product. 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 approaches for improving animal productivity and reducing GHG emission intensity. In subsistence production systems, reduction of herd size would increase feed availability and productivity of individual animals and the total herd, thus lowering CH_4 emission intensity. In these systems, improving the nutritive value of low-quality feeds for ruminant diets can have a considerable benefit on herd productivity while keeping the herd CH_4 output constant or even decreasing it. Residual feed intake may be a tool for screening animals that are low CH_4 emitters, but there is currently insufficient evidence that low residual feed intake animals have a lower CH_4 yield per unit of feed intake or animal product. Reducing age at slaughter of finished cattle and the number of days that animals are on feed in the feedlot can significantly reduce 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 should target increasing conception rates in dairy, beef, and buffalo, increasing fecundity in swine and small ruminants, and reducing embryo wastage in all species. Interactions among individual components of livestock production systems are complex but must be considered when recommending GHG mitigation practices.

Key words: greenhouse gas, livestock management, mitigation

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INTRODUCTION

Global analyses have clearly shown that non-CO_2 greenhouse gas (**GHG**) emissions [(i.e., enteric methane (**CH_4**) and nitrous oxide (**N_2O**)] are inversely related to animal productivity (Gerber et al., 2011). Higher producing animals consume more feed, produce more manure, and emit greater absolute amounts

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[1] This article is part of a series of articles examining methane and nitrous oxide mitigation practices for livestock operations. The article is derived in part from a published review of mitigation options for the livestock sector funded by the Food and Agriculture Organization (FAO) of the United Nations (Hristov et al., 2013b), with the consent of FAO. The views expressed in this information product are those of the authors and do not necessarily reflect the views or policies of FAO. The authors would like to thank the experts who reviewed the original report by Hristov et al. (2013b): M. Doreau, R. Eckard, D. Hongmin, T. McAllister, H. Montgomery, M. Powell, S. Sommer, and M. Tibbo.

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of GHG from enteric fermentation or during manure storage and application or deposition than low-producing animals. Converted per unit of animal product, however, higher-producing animals usually have lower GHG emissions than low-producing animals. Therefore, enhancing animal productivity is usually a successful strategy for mitigating GHG emissions from livestock production systems. Discussions presented in the current analysis are based primarily on a recent review of mitigation measures for livestock by Hristov et al. (2013b). The present paper is the third of a series of 3 reports and focuses on the analysis of published data on GHG mitigation options related to animal management, including improving animal genetics, fertility, and animal health and longevity. The first (Hristov et al., 2013a) and second (Montes et al., 2013) papers in this series address enteric CH_4 emissions and CH_4 and N_2O emissions from manure decomposition, respectively. Gerber et al. (2013) discussed interactions among mitigation practices. insert 'A summary of the animal management mitigation practices discussed in the current manuscript is presented in Table 1.'

ANIMAL MANAGEMENT MITIGATION PRACTICES

Enhancing Animal Productivity. Increase in animal productivity can be achieved through improvements in animal genetics, feeding, reproduction, health, and overall management of the animal operation. 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 with a reduced environmental footprint. Reduction in animal numbers was the single most influential mitigation strategy that significantly reduced the C footprint of the United States dairy industry (Capper et al., 2009). Similarly, with the milk quota system in the Netherlands, milk production per cow increased from 6,270 kg fat- and protein-corrected milk (**FPCM**)/yr in Kyoto base year 1990 to 8.350 kg FPCM/yr in 2008, with a concomitant decrease in CH_4 production from 17.6 to 15.4 g/kg FPCM, respectively (Bannink et al., 2011). Similar progress has been made by the pork industry. The number of hogs marketed in the United States increased by 29% between 1959 and 2009 whereas the size of the breeding herd decreased by 39%. Feed conversion efficiency increased by 33%, feed use decreased by 34%, and the C footprint per 454 kg of hot dressed carcass weight produced decreased by 35%. 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 during the same period from 775 to 1,828 kg (National Pork Board, 2012).

In the global context, particular attention must be placed on mitigating GHG emissions from developing countries. Europe, North America, and the non-European Union former Soviet Union countries produced 46.3% of ruminant meat and milk energy and only 25.5% of the enteric CH_4 emissions in 2005 (O'Mara, 2011). In contrast, Asia, Africa, and Latin America produced a similar amount (47.1%) of ruminant meat and milk energy but a large proportion (almost 69%) of enteric CH_4 emissions. Therefore, the Intergovernmental Panel on Climate Change (IPCC, 2007) estimated that about 70% of the global GHG mitigation potential from agriculture lies in developing countries (Smith et al., 2007). In developing countries, however, 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, the two constraints for increasing animal production in developing countries are the low genetic potential of the animals and the poor availability of quality feed. Undoubtedly, significant potential exists for increased production by better feed management and proper feeding in developing countries as well as for intensive production systems in developed countries. Using a partial life cycle assessment (**LCA**), Bell et al. (2011) demonstrated that improvements in feed efficiency and milk production [in their example, from about 23 to 28 kg energy-corrected milk (**ECM**)/d] can significantly reduce GHG emissions and land use of the dairy herd.

However, selection for high productivity should not be at the expense of other important traits, especially those traits critical for survival of livestock in the local environment (climate, feed resources, and diseases). With dairy cows, tradeoffs between selection for high milk production and decreased productive life, increased death rate, and decline in fertility need to be avoided (Hare et al., 2006; Miller et al., 2008; Norman et al., 2009). The survival rate to parity 2 by Holstein cows in the U.S. declined from 77.3% in 1980 to 74.1% in 2000 and survival rates to parities 3 and 4 declined from 56.6 in 1980 to 49.0% in 1999 and from 24.2 (in 1980) to 14.3% in 1997, respectively (Hare et al., 2006). With only 2 to 2.5 lactations, dairy cows cannot realize their production potential. As pointed out by Van Vuuren and Chilibrost (2011), the milk efficiency of dairy cows (i.e., milk energy output/feed energy input) increases exponentially up to 4 lactations. Impaired reproductive performance also has a significant impact on farm profitability and might not be fully compensated by increased milk production, as demonstrated by Evans et al. (2006) for commercial dairy herds in Ireland. Apart from productivity, however, management practices, such as improved animal health and fertility (Place and Mitloehner, 2010), in intensive production systems can improve overall animal performance and lifetime productivity. By some estimates, extended lactation (Van Amburgh et al., 1997; Auldist et al., 2007; Kolver et al., 2008; Grainger et al., 2009) can reduce enteric CH_4 emission from dairy production systems by 10% (Smith et al., 2007). However, this may not be a feasible alternative to a 12-mo 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 use of recombinant bovine somatropin (**rbST**; Annen et al., 2004; Rastani et al., 2005; Klusmeyer et al., 2009). This practice may not be suitable for all cows and all herds (Marett et al., 2011; Santschi et al., 2011). Pinedo et al. (2011), for example, reported decreased early lactation and 305-d milk yields and increased overall culling rate when the dry period was reduced or eliminated.

Progress in reducing GHG emission intensity (**Ei**; GHG per unit animal product) from ruminants in the developing countries can be achieved by increasing animal productivity. Gerber et al. (2011) demonstrated a great difference in GHG emissions depending on milk yield of dairy cows, with as much as a 10-fold variation between countries or regions with high and low milk yields. Flachowsky (2011) estimated that a dairy cow producing 40 kg milk/d would have about 50% lower CO_2–equivalent (**CO_2e**) emissions per kilogram of edible protein than a cow milking 10 kg/d. Similarly, emissions would be about 70% lower from beef cattle gaining 1.5 vs. 1.0 kg/d, 40% lower from a growing or fattening pig gaining 900 vs. 500 g/d, and 60% lower from a laying hen with 90 vs. 50% laying performance.

According to data for the dairy sector by the Food and Agriculture Organization (Gerber et al., 2011), in 2010 the annual milk production per cow for North America was approximately 8,900 kg and in South and Southeast Asia (**SEA**) 2,800 kg/yr for specialized dairy systems and 1,000 kg/yr for unspecialized systems. Using the Gerber et al. (2011) relationship for GHG emissions (CO_2e, kg/cow per yr = 0.8649 × milk yield, kg/cow per yr + 3,315.5, $r^2 = 0.79$, and assuming milk yield is as FPCM), a North American cow will produce about 11,000 kg CO_2e/yr and a SEA cow about 5,700 kg CO_2e/yr, which is 1.24 and 2.05 kg CO_2e/kg FPCM milk, respectively. If milk production in SEA is increased by 30%, the CO_2e output will decrease to 1.79 kg/kg milk. Similarly, Blümmel et al. (2009) estimated that increasing milk yield per animal in India from the national average of 3.6 L/d to up to 9.0 L/d was possible using currently available feed resources, and this would potentially reduce CH_4 production in that country from 2.29 to 1.38 Tg/yr. Another example of how increased productivity, through increased feed quality, can decrease enteric CH_4 Ei was provided by Waghorn and Hegarty (2011). These authors calculated that growing lambs on higher quality pasture (20% higher ME value) would result in greater gain and about 50% lower enteric CH_4 Ei.

Ruminant production systems based on concentrate feeds are reportedly more efficient from the animal perspective and emit less GHG per unit of product (Beauchemin et al., 2010; Pelletier et al., 2010). However, this may not be the case if all inputs are included in calculating GHG Ei for dairy production systems (Rotz et al., 2009) or intensive grain-finished vs. extensive, grass-finished beef systems (Pelletier et al., 2010; Waghorn and Hegarty, 2011), particularly when soil C storage in grasslands and land use changes are adequately considered. Improvement in animal nutrition through strategic use of available resources such as feeding a balanced diet based on the physiological needs of the animal, reducing feed wastages, increasing concentrate feed availability, and improving animal genetics have a tremendous potential 'to increase animal productivity in developing countries (Makkar, 2013).

Due to poor pasture quality, grazing management may not be a viable option for improving animal nutrition in many regions, in which case improvement in productivity must come through feeding preserved forages or concentrates. Because the growth in cereal grain production has generally followed the growth of world population (Hristov et al., 2013b) and because human nutrition is expected to improve in the developing world, it is questionable if more grain will be available for feeding ruminant animals. Growing ruminants are much less efficient in utilizing grain for BW gain than poultry or swine, but dairy cows can be as efficient (depending on the level of production) as monogastric animals in producing edible protein (Flachowsky, 2002, 2011; Gill et al., 2010; De Vries and de Boer, 2010). Whether increasing the inclusion of grain in the ration of ruminants can be an economically feasible strategy to increase milk and particularly meat production and thus reduce the environmental footprint of livestock is questionable in the long term. A challenging but more sustainable solution is to produce concentrate by strategically mixing agro-industrial by-products that are rich in energy or proteins (Makkar, 2013).

Within dairy production systems, grassland-based systems have been estimated to have generally higher (by about 50%) GHG emissions per unit of FPCM than mixed farming systems although some grazing systems in temperate regions have low GHG emissions (FAO, 2010). Organic dairy production systems have generally higher GHG Ei than conventional dairy systems (Heller and Keoleian, 2011; Kristensen et al., 2011). This may not always be the case, depending on the amount and type of fertilizer used for crop production and the level of animal productivity (Martin et al., 2010).

The environmental efficiency of pasture-based dairy production systems can be improved by a variety of best management practices (Basset-Mens et al., 2009; Beukes et al., 2010), 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.

Kennedy et al. (2001) 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 and concluded 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 authors also concluded 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.

Enhancing the genetic potential of the animal is critically important, but it is equally important not to import high genetic potential animals 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. However, importation of Holstein cows into regions that cannot provide the necessary nutritional, health, and physical environments to support their genetic potential for production 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 whereas in these conditions rearing the local cross-bred dairy cows has resulted in a substantial economic advantage for farmers.

Enhancing Animal Productivity by Improving the Nutritive Value of 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; Walli et al., 2012). Devendra and Leng (2011) and Tarawali et al. (2011) argued that interventions to improve the feeding value of low-quality feeds should be considered in the whole farm system context. In developing countries, the majority of farmers operate in smallholder mixed crop–livestock systems, and almost 3 billion people depend on such systems for their food supply (Herrero et al., 2010). Most livestock production systems typical of those areas are faced with one or more seasons with low feed availability and quality, and production during such seasons is nonexistent or even negative because animals rely solely on crop residues. During the cropping and harvesting season, more and better feeds are available, but labor limitations and grazing land availability may prevent optimal feeding (Tarawali et al., 2011; Owen et al., 2012). Importation of high quality feeds 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. In these systems, livestock intensification competes with crops for inputs of labor, capital, and land. 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.

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 productivity. Hence, CH_4 emissions will be reduced for both the total herd and per unit of animal product. However, 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.

Supplying a substantial amount of relatively good quality feed in 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 expectation for worldwide 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 investigation (Owen et al., 2012; Hristov et al., 2013b).

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 multinutrient 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 a source of CH_4 mitigating agents, that is, nitrates, is discussed in our companion paper (Hristov et al., 2013a). Calcium, P, Cu, and Zn are other nutrients that improve utilization of low-quality feeds. Limitations of those nutrients mostly occur when low-quality feeds are given as the sole feed. Whenever some green feeds or concentrates are available, 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) discussed options for treatment of crop residues. Rice or wheat straw, the crop residue in these publications, can be regarded as a proxy for other low-quality feeds. Chemical treatments [e.g., urea, ammonia ($\mathbf{NH_3}$) or sodium hydroxide] and biological treatments (direct by growing fungi on the straw or by administering fungal enzymes to the straw) 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% urea solution and stored airtight for at least 1 wk. 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, labor needs, and practical feasibility have led to poor adoption of these techniques (Schiere, 1995; Owen et al., 2012) despite decades of research and outreach 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. Even if socioeconomic circumstances benefited 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.

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 were not improved, which may explain why this technology was not adopted (FAO, 2011b). The loss of digestible DM and the decrease in the feeding value of the crop during this treatment can be dramatic, rendering the process unfeasible (Lynch et al., 2012).

Many farmers in extensive production systems recognize and consider straw quality in their decisions for crop cultivation (Parthasarathy Rao and Hall, 2003; Schiere et al., 2004; Parthasarathy Rao and Blümmel, 2010). Coarse straws (of millets, sorghum, and corn) 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 (Subba Rao et al., 1993; Grando et al., 2005; Blümmel et al., 2010). An advantage of breeding and selection over treatment is that no additional input of capital or labor is required. Increased use of crop residues for feeding may, however, reduce soil OM content (Tarawali et al., 2011). Breeding straw for improved feeding quality has already shown promise for increased production and reduced CH_4 intensity in southern India (Blümmel et al., 2010).

Recombinant Bovine Somatotropin. An animal management practice that can indirectly reduce emissions by improving productivity in dairy cattle is the use of rbST. Capper et al. (2008) used a mathematical modeling approach to estimate the effect of rbST use on individual cow- and industry-wide scales, assuming an increase in milk production of 4.5 kg/d (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% per unit of milk produced.

However, use of rbST 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, of cows failing to conceive, and of developing clinical signs of lameness (Dohoo et al., 2003). However, other large studies detected no decline in fertility with the use of rbST but did note reduction in the length of expressed estrus (Rivera et al., 2010). Furthermore, in a large multiherd study in the United States, rbST use did not increase the incidence, duration, or severity of mastitis nor increase the culling rate in the herds, but it was associated with a slight increase in foot problems not associated with lameness (Collier et al., 2001). Should the use of rbST have a negative influence on fertility and animal health, then the reduction in CH_4 emission estimated by Capper et al. (2008) would be smaller or even nonexistent. In addition, this mitigation practice is likely to be applicable only in intensively managed animal production systems.

Growth Promotants. Growth promotants of various types [ionophoric antibiotics (discussed in the companion paper; Hristov et al., 2013a), implants (hormones, melengestrol acetate, and trenbolone acetate), and β-agonists (ractopamine, the decrease in zilpaterol hydrochloride) are routinely used by the U.S. beef and pork industries to stimulate growth and partition nutrients, specifically energy, from fat to lean tissue deposition (Duckett and Owens, 1997). Similar to rbST, the effects of these compounds on GHG emissions from ruminants can be expected to come from increased growth rate (i.e., less time on feed to reach slaughter BW) and feed efficiency (Scramlin et al., 2010; Parr et al., 2011; Al-Husseini et al., 2013), thus reducing CH_4 Ei (Cottle et al., 2011). In monogastric species, increased feed efficiency will result in less manure excreted and, consequently, decreased GHG Ei. In beef cattle, the gains in feed efficiency can be remarkable, reaching over 15 to 20% (CAST, 2005). Assuming meat quality is not impaired (which may not be the case, according to some reports; Faucitano et al., 2008; De Almeida et al., 2012), the production and environmental benefits of these compounds are unparalleled. As with rbST, however, growth promotants are banned in many countries and their use will heavily depend on societal perception and acceptance.

Animal Genetics. Improvements in both genetic potential and diet management can lead to a significant reduction in GHG emissions per unit of product from livestock production systems, as shown for the Australian beef industry (Henry and Eckard, 2009). Beef cattle with low residual feed intake (**RFI**; defined as the difference between actual and predicted feed intake) can produce up to 28% less 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%), with lesser contributions from digestibility (10%), heat increment and fermentation (9%), physical activity (9%), and body composition (5%).

In an extended review of the topic, Waghorn and Hegarty (2011) concluded that there was little evidence that efficient animals have a different CH_4 yield per unit of DMI. Furthermore, they pointed out the need to select high-producing animals because this reduces emissions per unit of product. Similarly, Weber et al. (2013) reported no difference in CH_4 emissions between high- and low-RFI beef cattle. 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 individual animals that have a lower than average CH_4 yield requires that 1) the host animal controls its microflora and that the trait is heritable, 2) selection for low CH_4 producers is more important to animal producers than other traits (e.g., productivity, fertility), and 3) the effect is persistent and applicable to all levels of production. Therefore, 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 CH_4 production in the order of 11 to 26% is theoretically possible.

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 rumen 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., more efficient) animals.

Modern molecular techniques have revealed much greater diversity in the ruminal microbiota 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 CH_4 (McSweeney and Mackie, 2012). These authors indicated that, based on the analysis of global datasets, the majority (>90%) of rumen methanogens are affiliated with genera *Methanobrevibacter* (>60%), *Methanomicrobium* (approximately 15%), and a group of uncultured rumen archaea commonly referred to as rumen cluster C (approximately 16%; recent data have indicated that these methanogens produce greater amounts of CH_4 relative to *Methanobrevibacter*). Animal species, breed, and environmental conditions affect rumen microbial diversity, which could be used to select animals with lower CH_4 emitting potential or manipulate the rumen ecosystem to raise animals producing less CH_4 per unit of digested feed (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.

As indicated earlier, RFI selection is a promising technology but with uncertain returns. In addition, the current system for estimating RFI requires significant investments in animal identification and accurate measurements of feed intake and animal production unlikely to take place in developing countries in the short term (Waghorn and Hegarty, 2011). The concept of genetically modified animals, designed to have a lower environmental footprint (primarily by having higher feed efficiency), although not universally accepted, may offer an opportunity for more efficient animal production (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 by Solis et al. (1988) concluded that maintenance energy requirements for weight and energy balance 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 associated with altered nutrient partitioning. 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; Østergaard et al., 1990). It is recognized now that intensive selection for one genetic trait can lead to losses in other traits with negative correlations. 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). A Dutch study comparing Jersey cows against 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% (all forage and 50:50 forage:concentrate diets, respectively) for the Jersey group vs. 56 and 61% 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) performed 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). 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% more efficient than Holstein-Friesian cows). The authors also indicated that crossbred cows may have an advantage over purebreds due to improvements in feed efficiency, health, and fertility—partly due to heterosis. However, a more recent comparison between Holstein, Danish Red, and Jersey cows did not find a clear advantage of Jersey vs. Holstein (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). Jersey cows were about 172 kg lighter than the other 2 breeds. Body weight is an important factor contributing to GHG emissions through energy requirement for maintenance. Smaller breeds may have a smaller C footprint per head due solely to smaller BW. Capper and Cady (2012) estimated that the C footprint per 500,000 t of cheese produced would be 1,662 kt of CO_2e 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 on the importance of milk component yields compared with milk volume in relation to GHG emissions from the dairy industry is an interesting one. According to USDA Dairy Herd Information 2011 records (USDA, 2011), the average milk yield and milk fat and protein concentration for Ayrshire, Brown Swiss, Jersey, and Holstein herds in the United States was 7.020 kg/lactation with 3.84 and 3.14% fat and protein, 9,998 kg/lactation with 3.97 and 3.31% fat and protein, 8,638 kg/lactation with 4.70 and 3.62% fat and protein, and 11,812 kg/lactation with 3.67 and 3.04% fat and protein, respectively. Fat and protein yields per lactation can be calculated: 319 and 261 kg, 397 and 331 kg, 406 and 313 kg, and 434 and 359 kg, respectively. Thus, the Holstein breed has an 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 (including lactose, which is closely related to milk volume and does not contribute to cheese and butter yields). Fluid milk consumption in the United States represented 32% of all dairy products consumed in 2012 (USDA, 2012) The proportion of milk consumed as fluid milk is much greater in regions with high population density such as the Northeast and Mideast). 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. Therefore, dairy breeds with higher milk yield but lower concentration of milk components, such as the Holstein breed (outperforming 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 (cheese manufacturing has a greater environmental impact, primarily through energy consumption, than fluid milk; Milani et al., 2011) 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.

Even in developing countries where feed resources may be limited, introducing genes for high production may be beneficial. A large survey of smallholder dairy farms (average milk production was 1,425 L/lactation) in the "drier transitional zones" of Kenya showed that exotic dairy breeds (Friesian, Ayrshire, Guernsey, and Jersey) adapted to the conditions of the survey regions and were economically more efficient than the indigenous breeds (Sahiwal, Boran, Zebu, and Zebu cross; Kavoi et al., 2010). A 3-yr study in Switzerland investigated the performance of New Zealand Holstein Friesian cows under Swiss grazing conditions (60 to 65% of the diet was grazed pasture) in comparison with indigenous Swiss breeds. 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 or "sexed" semen technology. Application of this technology in the dairy industry could 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 sexed semen technology for producing heifers is of particularly high importance in reducing the number of dairy animals in countries such as India where cattle are not slaughtered due to religious reasons (Harinder P.S. Makkar, unpublished data, 2012). Higher cost and lower conception rate are limitations to adoption of use of sexed semen (Weigel, 2004).

Animal genetics can also have a significant effect of GHG emissions from swine and poultry. As relatively little enteric CH_4 is emitted from these animals, the majority of the GHG from swine and poultry operations (excluding feed production) are attributed to manure in housing facilities and storage and following land application. Therefore, improving animal feed conversion efficiency, that is, reducing the volume of manure produced while maintaining animal productivity, becomes a major strategy for mitigating CH_4 and nitrous oxide (**N_2O**) emissions from these farm species. Animals from genetic lines predisposed to high feed efficiency excrete fewer nutrients in urine and feces. Healthy herds also use feed efficiently and can reduce N excretion by 10% compared with unhealthy herds. Split-gender feeding enables producers to feed each gender closer to its nutritional requirements; for example, turkey hens require less nutrients due to their smaller size than male turkeys (Pennsylvania State University Extension, 2013).

A study with 380 Duroc boars from 7 generations and 1,026 Landrace pigs from 6 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 4 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 had moderate h^2 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.

Animal Health and Mortality. Improving animal health and reducing animal morbidity and mortality to improve efficiency of the animal production system offer opportunities to reduce both CH_4 and N_2O from enteric fermentation and animal manure. Although connections among animal health, mortality, and productivity are obvious, few studies have examined their implications on GHG emissions (Hospido and Sonesson, 2005; Bell et al., 2008; Dourmad et al., 2008; Stott et al., 2010). The GHG emissions 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. The opportunities to reduce GHG emissions from animal manure through improving animal health and reducing mortality are especially important in places where the livestock production system is rudimentary or the manure application and dissemination technologies are unavailable or difficult to implement.

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 programs 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 GHG emissions per unit product. Taking the dairy industry as an example, lameness or injury (20.0%), mastitis (16.5%), and calving problems (15.2%) represent the 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 GHG emissions per unit of product. Similarly, reproductive problems (26.3%), mastitis (23.0%), poor production (16.1%), and lameness or injury (16.0%) are major reasons for permanently culling cows from the United States dairy herd (USDA, 2007). According to LeBlanc et al. (2006), 75% of disease occurs within the first month after calving. In addition, 26.2% of dairy culls were reported to occur from 21 d before to 60 d after calving in a study of 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 modeling 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 in the environmental impact of 2.5 (global warming potential) to 5.8% (depletion of abiotic resources) if the clinical mastitis rate decreased from 25 to 18% and the subclinical mastitis rate decreased from 33 to 15% in Spain.

ANIMAL FERTILITY

Data from the literature on animal fertility are summarized in Table 2. Poor fertility increases GHG emissions from animal production systems (Dyer et al., 2010; O’Brien et al., 2010; Crosson et al., 2011); primarily, poor fertility causes livestock producers to maintain more animals per unit of production and keep more replacement animals to maintain herd or flock size (Garnsworthy, 2004; Berglund, 2008; Wall et al., 2010; Bell et al., 2011). Garnsworthy (2004) concluded that improvements in fertility could reduce CH_4 emissions by 24% and NH_3 emissions by 17%, 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 yr is estimated to be associated with genetic selection for production and increases in inbreeding (Shook, 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 on good management practices 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, 2011), sire mate selection from highly fertile animals, reducing stressors, and improving education on the factors influencing fertility (Banda et al., 2011).

Use of reproductive technologies where they are available and cost effective, such as genetic and genomic selection for fertility (Tiezzi et al., 2011; Amann and DeJarnette, 2012), AI (Lopez-Gatius, 2012), gender-selected semen (i.e., sexed semen; Rath and Johnson, 2008; DeJarnette et al., 2011), embryo transfer (Hansen and Block, 2004; Longergan, 2007), and estrous or ovulation synchronization (Gumen et al., 2011) increases reproductive efficiency and reduces the number of animals and GHG Ei (Garnsworthy, 2004; Bell et al., 2011). In particular, failure to use 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, 2011b).

Choice of Breed and Mating Strategies. Indigenous breeds reflect 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 color, tail type, and presence and type of horns (Duguma et al., 2010; Gizaw 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 nonadapted 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 and regional environment and with consideration to local preferences as well as infrastructure, personnel (management skills), and feed resources.

The trend in recent years has been to take a crossbreeding approach using nonadapted 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 program to accelerate genetic progress. Although this can result in slower gains in pro-

Table 1. Animal management strategies offering non-CO_2 greenhouse gas emission intensity reduction

Category	Species[1]	Effect on productivity	Potential CH_4 mitigating effect[2]	Potential N_2O mitigating effect[2]	Effective[3]	Recommended[4]
Increased productivity	AS	Increase	High[5]	High[5]	Yes	Yes
Recombinant bovine somatotropin	DC	Increase	Low	?[6]	Yes?	Yes?[7]
Growth promotants	BC and SW	Increase	Medium	Low	Yes	Yes[7]
Genetic selection (residual feed intake)[8]	BC, DC, and SW	None	Low?	?	Yes	Yes?[9]
Animal health	AS	Increase	Low?	Low?	Yes	Yes
Reduced animal mortality	AS	Increase	Low?	Low?	Yes	Yes
Reduced age at harvest and reduced days on feed	AS[10]	None	Medium	Medium	Yes	Yes

[1] DC = dairy cattle; BC = beef cattle (cattle include *Bos taurus* and *Bos indicus*); SW = swine; AS = all species.

[2] High = ≥30% mitigating effect; Medium = 10 to 30% mitigating effect; Low = ≤10% mitigating effect. Mitigating effects refer to percent change over a "standard practice", that is, study control that was used for comparison and are based on combination of study data and judgment by the authors of this document.

[3] Determined on the basis of greenhouse gas 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] Increased productivity will have a powerful mitigating effect on greenhouse gas 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.).

[6] ? = uncertainty due to limited research, variable results, or lack or insufficient data on persistency of the effect.

[7] Depends on national regulations.

[8] Residual feed intake × nutrition interaction apparent with CH_4 reductions occurring in high quality diets or pastures.

[9] Uncertain results and requires significant investment; probably impractical for many developing countries.

[10] Meat animals only.

duction 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 culturally appropriate appearance traits. For example, Mirkena et al. (2012) described 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, nongovernment organizations, or academic institutions can establish nucleus flocks for distribution of high quality genetics. Using these approaches yielded significant gains in both lambs born and weaned per ewe (Mirkena et al., 2012), but the authors concluded the approach relied on accurate pedigree and performance information and a commitment of continuing support for the program.

In many countries, including many developed countries, pure-breeding is used extensively for genetic improvement and providing founder animals for effective crossbreeding programs, if careful attention is paid 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 and productive life) with evidence of success (Kuhn et al., 2006; VanRaden et al., 2007; Norman et al., 2009).

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). Whereas 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). Whereas 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, approximately 75% 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 use the same male even as his own daughters reach breeding age (Zi, 2003). Education and temporary mixing of flocks or 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, which 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

Table 2. 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]
Mating strategies			
Crossbreeding	ARand SW	High	Low
Reduced inbreeding[4]	AR and SW	Medium	Moderate
Genomic selection for fertility	AR and SW	Medium	High
Improved productive life			
Early puberty	AR and SW	Medium	Moderate
Early weaning	AR and SW	Medium	Moderate or high
Reduce seasonality	AR and SW	Medium	Moderate
Enhanced fecundity[5]			
Increased litter size	SW, SH and GO	High	High
Increased litter/yr	SW, SH and GO	High	High
Prolific breeds	SW, SH and GO	High	Low
Gene introgression	SW, SH and GO	High	High
Extended breeding season	SH and GO	Medium	Moderate or low
Periparturient care and health			
Shorten dry period	DC	Medium	Low
Increase dry matter Intake	DC	Medium	Moderate
Dietary lipids	AR	Medium	High
Vaccination	AR and SW	Medium	Moderate
Reduction of stressors			
Heat	AR and SW	High	Low/moderate
Handling and transport	AR and SW	Medium?	Moderate or low
Disease	AR and SW	High	Moderate/high
Nutrition	AR and SW	High	Moderate
Assisted reproductive technologies[6]			
Artificial insemination	AR and SW	High	Moderate or high
Hormonal synchronization	AR and SW	Medium	High
Embryo transfer	AR and SW	High	High
Sexed semen			
Pregnancy diagnosis	AR	High	High

[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% 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%. Based on combination of study data and judgment 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 or modest facility improvements; enhanced resources or training needed.

[4] Estimates represent estimates of inbreeding of 20% in purebred sheep (Ercanbrack and Knight, 1991) and of 5 to 15% in dairy cattle (Soares et al., 2011; Panetto et al., 2010). Each 1% increase in inbreeding in sheep results in a 1% decline in lambs weaned per ewe. Average inbreeding coefficients in purebred sheep breeds was 20 to 30% (Ercanbrack and Knight, 1991).

[5] 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%. 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% of production (remaining 60% are smallholder or backyard operations). If applied to the remainder of production, the effect would be significantly greater (China National Swine Industry Association, 2008).

[6] Potential decrease in animal numbers: >5%; potential CH_4 and N_2O mitigating effect, 3.5 to 5.5%. Estimates represent 14 million fewer replacement dairy animals needed with a 5% increase in dairy conception rate. This will also increase lifetime milk production and, potentially, productive life.

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 or flocks, and more pregnancies during the animals' productive life (Place and Mitloehner, 2010). 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 or kiddings in 1 yr, effectively doubling production per female (Notter, 2008). However, these types of accelerated lambing systems require intensive management, adequate facilities, 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 or strains of animals can greatly increase the efficiency of production by increasing the number of animals (or BW) weaned per female for each gestation. However, breed choice must meet the requirements for appearance traits, adaptation to regional climate, feed, and production and management practices (Getachew et al., 2011). This approach is relevant for small ruminants and less relevant to cattle production because twins are generally not favored due to the resulting increase in periparturient problems (dystocia, uterine infection, or delayed resumption of cyclicity).

Several sheep breeds (e.g., Finnsheep, Romanov, Boorola Merino, etc.) 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 used 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% increase in productivity of ewes carrying the *FecB* gene (FAO, 2011a). However, success of this program 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 programs aimed at increasing fecundity. Crossbreeding and gene introgression programs using prolific breeds have proven their ability to increase fecundity and BW 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 in small ruminants (Fitz-Rodríguez 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 2 to 3 wk before and into the breeding season. With such nutritional strategies, improvements in ovulation rate of 0.5 to 1 have been reported (Naqvi et al., 2012). The combined use of early introduction of males and flushing increased 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 overly fat (e.g., are thin).

Early Weaning. To maintain a yearly calving interval, beef cows must rebreed within approximately 85 d 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 used. For example, 12 h 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 3 to 4 wk, wean that litter, and then return to estrus and be rebred within 4 to 8 d (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 (Beever, 2006; Thatcher et al., 2006; Gumen et al., 2011). 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 systems (Beever, 2006; Thatcher et al., 2006; Gumen et al., 2011).

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 d and, in fact, recent work suggests a dry period of 30 d 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 switch to omega-3 fats (anti-inflammatory) at 30 d postpartum 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 before 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% 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 postmortem disease diagnosis in developing countries.

Reduction of Stressors. Environmental stressors (heat, transport, predation, feed and water contamination, etc.) have been shown to cause embryo loss, especially in the first 4 to 6 wk after mating and insemination (Hansen and Block, 2004). Management strategies can reduce stress during early gestation. Provision of adequate access to shade and water can reduce heat stress and minimizing transport or herding of animals over long distances during the first 4 to 6 wk of gestation.

Assisted Reproductive Technologies. Artificial insemination and other reproductive technologies (estrus synchronization, embryo transfer, and gender-selected semen; De Vries et al., 2008) can be used to enhance the genetic value of offspring, particularly relative to fertility traits. For example, AI improved several measures of fertility compared to natural mating when implemented as a program to improve the efficiency of smallholder swine production in Thailand (Visalvethaya et al., 2011). In addition, 55% of smallholder dairy farmers in Malawi reported using AI (Banda et al., 2011). However, success of AI programs was dependent on distance from access to semen, good quality equipment, training of inseminators, heat detection skills, 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 programs designed to synchronize estrus or ovulation are credited, in part, with the apparent reversal of declining fertility seen in North American dairy systems during the last decade. These programs 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%) reported using pregnancy diagnosis, but this generally occurred 90 d 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 approaches are associated with large errors, particularly if farmers have few cows and they are housed individually (nongrazed) as is often the case.

CONCLUSIONS

Recommendations for animal and reproductive management mitigation practices discussed in this review are summarized in Tables 1 and 2.

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 improved local breeds and/or of crossbreeds are recommended approaches for improving animal productivity and reducing GHG emissions per unit of product. Selection for high productivity should not be at the expense of other important traits such as reproduction and animal health.

Enhanced animal productivity and feed efficiency with metabolic modifiers, such as rbST and growth promotants, would reduce GHG Ei but applicability of this mitigation practices is limited to regions where the use of these compounds is permitted and where feed, facility, and management resources are available to meet the needs of high productivity.

Improved animal health and reduced mortality and morbidity are expected to result in increased animal productivity, diluting GHG emissions per unit of product.

Mitigation options that improve the nutritive value of low-quality feeds in ruminant diets could have beneficial effect on individual animal productivity, which, provided that the total herd size is not increased (and preferably is reduced), will increase herd productivity while keeping herd CH_4 output constant. Consequentially, CH_4 Ei will be decreased. The reduction of the herd size itself can result in concomitant reduction of herd CH_4 emission and increased herd productivity as better feed materials are fed to animals. Constraints to the application of mitigation options such as chemical treatment, supplementation, breeding and selection for straw quality, and reduction of herd size are mainly economic and sociocultural. Suggestions to overcome these constraints have been discussed in FAO (2011b). Technically, these treatments can easily be applied. However, despite a long history of research to treat low-quality feeds, there has been little adoption of these practices on farms.

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 nonruminants. 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.

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 should 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 fewer replacement animals needed, fewer males required where AI is adopted, longer productive life, and higher production per breeding animal.

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