Nutritional and flock management options to reduce methane output and methane per unit product from sheep enterprises

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Abstract. The daily methane output of sheep is strongly affected by the quantity and digestibility of feed consumed. There are few widely applicable technologies that reduce the methane output of grazing ruminants without limiting feed intake per head or animal numbers. In contrast, there are many opportunities to increase the amount of animal product generated per unit of feed eaten. These include improving growth and reproductive rates of livestock and will reduce methane emission per unit of product (called emissions intensity) for individual animals. Producer responses to such improvements through changes to stocking rate and total area grazed will have a major effect on the total emission and profitability of the enterprise. First mating of ewes as lambs (~7 months of age) rather than as hoggets (~19 months of age) reduces the emissions intensity of self-replacing flocks but not that of flocks for which replacement ewes are purchased. Selection of sheep for improved residual feed intake reduces emissions intensity at the individual animal level as well as at the enterprise level. At present, emissions policies that motivate farm managers to consider generating fewer emissions rather than more profit or product are lacking.

Additional keywords: animals, enteric methane, greenhouse gases, mitigation.

Introduction

Livestock production is associated with the release of methane produced by anaerobic microbial metabolism in the digestive tract and in manure, and also release of nitrous oxide from agricultural soils (Moss et al. 2000); both are greenhouse gases. In Australia, enteric methane from livestock constitutes 65% of total agricultural greenhouse gas (GHG) emissions, which renders ruminant livestock industries highly vulnerable to carbon trading systems in which a financial penalty is associated with GHG emissions (CIE 2009). Although the contribution of anthropogenic emissions to short-term climate variability and long-term climate change is not universally accepted, industries must now strive for economic viability in an impending carbon-constrained economy. Reviews of developing methane mitigation technologies are available (Moss et al. 2000; McAllister and Newbold 2008; Buddle et al. 2010). In this paper, we augment these reviews with a review of the effects of nutrition on enteric methane emission. We also review current opportunities for directly and indirectly selecting ruminants for lower enteric emissions and discuss these strategies in the context of opportunities for reducing total farm emissions and emissions intensity through livestock management.

Nutritional regulation of methane production

The ruminant industries strive to improve the conversion of pasture dry matter (DM) into animal product. This conversion efficiency incorporates both harvesting efficiency (the ratio of DM grown to DM consumed) and the efficiency of conversion of consumed DM into animal product. The effect of differences in feed digestibility on daily methane production (DMP) is confounded with associated changes in DM intake (DMI) in animals that consume feed ad libitum. In the following sections, we discuss the relationships between feed intake, feed quality and DMP and opportunities for nutritional manipulation.

Interrelationships between methane, feed intake and feed digestibility

It is not possible to give a single statement that correctly describes the effect of feed quality and intake on DMP and animal liveweight gain (LWG), so GrazFeed V5.02 (Freer et al. 2010) was used to simulate these outputs. To demonstrate the range of relationships, the example of a 30-kg Border Leicester × Merino wether lamb offered ad libitum access to a roughage containing 55, 65, 75 or 85% digestible DM was modelled (Fig. 1). The diet contained sufficient nitrogen to satisfy the requirements of the rumen microbes and the 4-month-old weaner lamb. Scenarios were modelled assuming a mature ewe weight of 55 kg and methane yield (% of gross energy) as estimated by Blaxter and Clapperton (1965) and multiplied by gross energy intake within GrazFeed to estimate DMP. The following trends are evident from Fig. 1.

- An increase in DMI is associated with an almost linear increase in LWG, but the rate of LWG is greater for feeds of greater digestibility (Fig. 1a).
An increase in DMI is associated with an increase in DMP. For diets of low to moderate digestibility, such as those consumed in extensive grazing systems in Australia, the methane released per unit additional intake is greater than when high intakes of high-digestibility feed are consumed (Fig. 1b).

DMP per unit metabolisable energy intake is lowest for diets with high-energy densities (Fig. 1c).

Although an increase in the intake of any diet reduces the emissions intensity of growth (g methane produced per kg LWG), emissions intensity at any given DMI is less for high-digestibility feeds than for low-digestibility feeds (Fig. 1d).

Small changes in energy intake result in small changes in methane output, but in large changes in animal performance. For example, assuming that the 30-kg lamb used in the model consumed 900 g/day of forage, an increase in digestibility from 65 to 75% would increase LWG from 51 to 101 g/day but would increase methane output by less than 1 g/day and almost halve emissions/unit LWG.

Nutritional manipulation of methane production

It is implicit from Fig. 1 that dietary factors, particularly the type of dietary carbohydrate, which will affect DM digestibility, will therefore affect DMP and methane production per kg of DMI. Consequently, the DMP of grazing livestock can be expected to change as the season changes, although this does not always occur with either pastures (Pinares-Patiño et al. 2003) or forages (McGeough et al. 2010). In addition to the abovementioned factors, specific dietary components or additives may reduce emissions and these are addressed below.

Lipids

Meta-analysis on the effects of supplementary lipid concluded that methane per kg of DMI is reduced by 6% for every 1% fat added to the diet (Beauchemin et al. 2008). More recent review of the component experiments indicated a lower response of 3.5% reduction in methane/kg DMI per 1% dietary lipid (Moate et al. 2010). However, this effect is variable and is typically less for high-fibre diets than for high-energy diets (Machmüller et al. 2001). Australian research has shown that methane yield can be reduced by including white cottonseed as an oil and protein source in dairy cattle diets (Grainger et al. 2008a) and cottonseed meal in beef cattle diets (Klieve et al. 2009). However, the reduction in DMP reported by the aforementioned authors was substantially less than the 6% per 1% oil added of Beauchemin et al. (2008).

The inclusion of more than 7% fat in cattle diets usually causes scouring and is not recommended. There has been little consideration of practical levels or methods of lipid supplementation in sheep, in contrast to abundant studies for dairy and beef cattle.
Tannins

Condensed tannins (CT) are components of plant defences against predators and pathogens. As CT have antimicrobial properties, they may reduce methanogenic activity in the rumen of cattle (Grainger et al. 2009). It has been shown that consumption of plants with high levels of condensed tannins by ruminants reduces methane yield per kg DMI (Woodward et al. 2004). There is considerable interest in selecting plant species such as clover and lucerne for high tannin levels, but there are two caveats to this approach. First, CT are generally antinutritive for ruminants: high CT intakes reduce protein and energy availability and thus animal performance (Kumar and Singh 1984). Second, the CT are chemically diverse and not all CT are equally effective in reducing methane generation (Beauchemin et al. 2007). Determination of dietary inclusion levels of CT that reduce DMP without compromising protein or carbohydrate availability is a challenging approach to methane mitigation but should be pursued, both as a possible supplement and as a potentially useful inclusion in pasture species.

Legumes

Consumption of legumes by ruminants results in a lower methane yield (methane produced per kg DMI) than consumption of grasses (Waghrum et al. 2002; McCaughey et al. 1999). This may arise due to the CT content of some legumes such as Sulla (Woodward et al. 2004) and leucaena but may also be due to the differing components in legumes, such as a higher pectin content. However, the voluntary intake of legumes, at least by sheep, is higher than that for grasses of the same digestibility (Freer and Jones 1984). Consequently, although consumption of legume-rich pastures by grazing livestock results in higher growth rates and lower emissions intensity, the absolute reduction in emission may be small.

Monensin

Monensin has been used extensively to manipulate rumen activity in cattle but is not currently registered for use in sheep. Although numerous short-term studies have shown that monensin decreases methanogenesis, long-term studies in Australia (Grainger et al. 2008b) and New Zealand (Waghrum et al. 2008) on dairy cows fed fresh forage have shown that monensin supplementation via a commercially available intraruminal controlled-release device does not suppress methane emission. In contrast, monensin delivered via this device had a sustained effect on methane emission from dairy cattle fed total mixed rations (Odongo et al. 2007). Variable persistence of monensin’s methane-suppressing activity may be due to the development of resistance to the antibiotic as observed for gram-positive fermentative bacteria (Newbold et al. 1993). While methanogens have not been screened for acquiring resistance to monensin, strains of rumen methanogens do differ in susceptibility to monensin (Chen and Wolin 1979) and prolonged use of the antibiotic, especially on forage-based diets, may simply select for non-susceptible strains.

Alternative hydrogen acceptors

During methanogenesis, hydrogen present in the rumen is used to reduce carbon dioxide to methane. Reactions that compete with methanogenesis for hydrogen are being investigated as a means of reducing DMP. A range of potential reactions that are thermodynamically more favourable than methanogenesis are summarised below (after Decker et al. 1970).

\[
\text{HCO}_3^- + 4H^+ + H_2 \rightarrow CH_4 + 3H_2O\Delta G_0 = -32.3 \text{kcal/reaction}
\]

\[
\text{Acrylate}^- + H_2 \rightarrow \text{propionate} \Delta G_0 = -18.2 \text{kcal/reaction}
\]

\[
\text{Lactate}^- + H_2 \rightarrow \text{propionate} \Delta G_0 = -19.6 \text{kcal/reaction}
\]

\[
\text{Malate}^- + H_2 \rightarrow \text{succinate} \Delta G_0 = -19.7 \text{kcal/reaction}
\]

\[
\text{SO}_4^2- + 2H^+ + 4H_2 \rightarrow H_2S + 4H_2O \Delta G_0 = -36.8 \text{kcal/reaction}
\]

\[
O_2 + 2H_2 \rightarrow 2H_2O \Delta G_0 = -113.4 \text{kcal/reaction}
\]

\[
\text{NO}_3^- + 2H^+ + 4H_2 \rightarrow \text{NH}_4^+ + 3H_2O \Delta G_0 = -143.5 \text{kcal/reaction}
\]

Organic acids such as fumarate and malate have been shown to reduce methanogenesis (Callaway and Martin 1997) and encapsulation may represent a feasible, if expensive, mode of delivery of organic acids (Wallace et al. 2006). Nitrate supplementation has also been investigated as a means of reducing methanogenesis (Leng 2008; Nolan et al. 2010), but care is needed to ensure that nitrite accumulation does not result in nitrite toxicity. Assuming 1 mol of nitrate reduced to ammonia decreases methane emission by 1 mol, ~30 g of calcium nitrate tetrahydrate/day would be required by sheep to reduce daily emissions (20 g/day) by 20%. This is a large amount of material to be expecting sheep to consume from a lick-block while grazing, although softer blocks could be developed. Introduction or stimulation of microbes that are capable of utilising the reductive acetogenesis (RA) pathway is an approach that redirects hydrogen away from methanogenesis without the need for continuous supplementation. Over nine genera of bacteria capable of reducing methanogenesis in vitro have been identified (Cook et al. 2009) indicates the possibility of this process occurring in a through-flow fermentation system such as the rumen.

Manipulation of animals to reduce methane emissions

Vaccination

Vaccination is considered one of the most appropriate ways of reducing emissions by ruminants in extensive grazing environments that offer little prospect of sustained dietary manipulation. The ability of animals to form antibodies in response to injection with crude methanogen extracts has been demonstrated, as has the ability of these antibodies to inhibit methanogenesis in vitro (Wright et al. 2004; Cook et al. 2008). However, the majority of vaccine formulations based on crude methanogen cultures have failed to reduce methane emissions from sheep (Wright et al. 2004; Williams et al. 2009) but do change the balance of methanogen species present (Williams et al. 2009). Vaccines based on specific antigenic components that are widely conserved across rumen methanogens (Cook et al. 2008)
are being developed in New Zealand. These also show an ability to agglutinate methanogens and reduce methane production by methanogen cultures (Wedlock et al. 2010) but have not been tested for efficacy in reducing emissions in sheep in vivo at this time. If successful this technique may enable long-term reduction in methane emissions from sheep and cattle in extensive grazing environments by infrequent vaccination that could coincide with other sheep management activities.

**Genetic selection for improved residual feed intake**

Selection for residual feed intake (RFI) is a feasible means of reducing the DMP of sheep. Animals superior for RFI consume less feed than average for their liveweight (LW) and level of performance. By definition, selection for RFI is independent of, and provides no selection pressure for, either LW or LWG. RFI is moderately heritable and selection of cattle for RFI has been shown to reduce DMI, and methane output may also be reduced (Nkrumah et al. 2006; Hegarty et al. 2007). Research is underway in Australia, New Zealand and Canada to confirm DMP differences among animals differing in RFI. Modelling of the effect of selection of sheep for RFI (Alcock and Hegarty 2010) within GrassGro® showed that the greatest reduction in emission intensity would occur in self-replacing Merino flocks and that a lesser reduction in emission intensity would occur in enterprises producing lamb meat. A larger grazing population can be supported by using sheep with lower RFI, but the GrassGro simulation of Alcock and Hegarty (2010) identifies possible unexpected consequences. RFI is typically measured in animals fed ad libitum, but in many extensive grazing situations feed is often not available ad libitum, and pasture availability limits feed intake. The GrassGro model indicates that when grazing, more feed-efficient ewes (low RFI) will not eat less than high RFI sheep, but will accumulate more body fat from what they do eat, and that this will lead to enhanced fertility and so more lambs/ewe, necessitating that fewer rather than more of the feed-efficient ewes can be grazed on the same available pasture. Consequently, the modelled reduction in total emission was less than that in emissions intensity, but the total emission was nonetheless reduced by nearly 6% from 10% improvement in RFI.

**Breeding for reduced methane yield and output**

Variation between individual sheep and cattle in the yield of methane per unit of DM consumed represents another opportunity for reducing emissions (Pinares-Patiño et al. 2003, 2010; Goopy et al. 2006). This trait is considered desirable because its use will reduce national emissions without changing the amount of DM consumed by livestock (H. Clark, pers. comm.). In some cases, individual sheep showing low methane yield have not sustained this characteristic over an extended time or when diet has changed (Pinares-Patiño et al. 2005; Vlaming et al. 2008). Recently, a select number of sheep exhibiting persistent differences in methane yield have been identified (Pinares-Patiño et al. 2010). Research to determine the repeatability and heritability of the yield of methane per unit of DM consumed is planned in Australia and New Zealand. Subject to economic enticements and penalties, genetic improvement for a methane trait, be it DMP or methane per unit DM intake, is desirable and should be pursued. It offers one of the few ways of modifying emissions from sheep in the extensive grazing environment where nutritional management is impractical.

Precise estimation of genetic parameters requires large datasets of individual animal records, but making so many measurements has not been feasible until recently. Goopy et al. (2009) observed that methane production by sheep during any given 2-h period is highly correlated with total methane production over the entire day ($r^2 = 0.5–0.82$), suggesting that short-term measurements of methane production may provide a means of defining the methane phenotypes of large numbers of sheep. Subsequently, a static respiratory chamber for measuring methane production over 1 h (1hMP) was developed (Fig. 2). Because no air flow is required for this short period of confinement, multiple chambers can be manufactured and individual emissions from up to 75 sheep can be recorded per day (15 chambers × 5 periods × 1 h). The repeatability of 1hMP (unadjusted for liveweight) is ~47% (Robinson et al. 2010). DMP measurements in open-circuit respiration chambers were compared with the 1hMP of the same sheep in static confinement immediately after the DMP measurement. The phenotypic correlation coefficient between 1hMP and DMP was 0.51 (Goopy et al. 2010). Measurements of 1hMP were made for 708 non-pregnant mature ewes, which were the progeny of 20 sires (mean, 35 progeny per sire). The method used in initial genetic studies involved an overnight fast followed by access to a familiar feed for 1 h before measurement. The heritability of 1hMP, adjusted for sheep liveweight, was 0.13 (Robinson et al. 2010); the genotypic and phenotypic relationships of 1hMP with growth and wool parameters will soon be examined. The pre-measurement protocol for determining 1hMP is currently being optimised (J. Goopy, 2010).
pers. comm.), including testing its repeatability on animals fasted overnight or those measured straight from the paddock. Use of a selection tool of such repeatability for a trait of this heritability clearly limits the rate of genetic gain that can be achieved. However, faecal worm egg count in sheep is a trait of comparable heritability with an animal test of comparable repeatability (Pollott et al. 2004) and yet phenotypic improvement has been made in sheep selection lines, achieving a realised annual genetic gain for estimated breeding value of worm egg count of 2.7% per annum since 1987 (Karlsson and Greeff 2006). It is planned to make short-term emission measurements on ~2000 performance-recorded mature sheep within the Sheep Cooperative Research Centre’s information nucleus flock to obtain estimates of heritability of methane production rate and of its genetic and phenotypic correlations with productivity traits.

One limitation to the application of short-term measurements in static chambers in the field is that pre-measurement intake of the animals is unknown, consequently methane yield cannot be calculated or used for selection from this measurement alone. Arguably the appropriate methane-specific breeding objective for the sheep industry would be methane per annum per sheep, in like manner to fleece per annum or LW at a particular age. While feed intake is a strong determinant of both wool and liveweight production, no knowledge of (or adjustment for) intake has been required to make genetic progress in these traits in the national flock.

Alcock and Hegarty (2010) used the farm system model GrassGro to model the effect of changing the genetics of sheep to animals producing 10% less methane/day. This was achieved by reducing methane yield as predicted by Blaxter and Clapperton (1965) by 10% but with no allowance for extra metabolisable energy being available to the sheep. A direct 10% reduction in individual animal and whole-flock emissions was achieved with no change in stocking rate. Genetic improvement in RFI (10%) was also emulated by increasing the efficiency of energy use for maintenance and growth (km kg). Genetic improvement in lamb growth (10%) was emulated by increasing standard reference weight of ewes and a growth coefficient in GrassGro. If all implemented together, selection for animals having 10% genetic superiority in DMP and RFI and lamb growth was estimated to lead to a reduction in whole-flock emissions of 18%. This was in a scenario where stocking rate was allowed to change to ensure that the flock only required supplementary feeding in 30% of years to keep ground cover at 70% or above.

Restructuring the livestock enterprise to reduce emissions and emissions intensity

Any strategy that reduces the proportion of dietary energy expended on animal maintenance will reduce emissions intensity (the quantity of methane generated per unit of meat, milk or wool produced). Such strategies include improvement of reproductive performance and nutritional and health management changes that minimise production constraints.

Management options for reducing the emissions intensity of a New Zealand self-replacing flock were assessed by Cruickshank et al. (2009). These authors applied relationships between traits measured over 6000 ewes and 8000 lambs in a research flock to simulate the impact of management changes on methane production per lamb sold from a hypothetical 1000 ewe flock. Total feed consumed by the flock was held constant as was methane yield at 16.8 g methane/kg DM intake and all lambs were sold at a weight to provide an average 17.4-kg carcass. The three most effective management strategies for reducing methane production per lamb sold were to increase the culling age of ewes (6.4% reduction by retaining for 6 not 5 years); increasing the conception rate of ewes (as determined by ultrasonic scan in utero; 7.8% reduction/10% unit increase), and lambing of ewes as hoggets rather than 1 year later (11.7% reduction). Increasing culling age of ewes from 5 to 6 years allowed the number of replacement hoggets to be reduced by ~40, with a corresponding rise in mature ewe numbers. Increasing the conception rate of pregnant ewes by 20% units from 1.6 to 1.8 lambs per ewe, such as may be achieved by using more fecund breeds or by selection within a breed, required ewe number to be reduced by ~70 ewes on account of the greater lamb numbers arising and their feed consumption. First mating of ewes to lamb out as hoggets rather than a year later reduced the replacement and breeding ewe numbers by ~20 and 70 ewes respectively but increased lamb number by over 100, so reducing the methane/lamb by an average of 13.6%.

Recent Australian modelling showed that the joining of maiden ewes at a younger age reduces emissions intensity in self-replacing flocks, but not in flocks for which replacement ewes are purchased (Alcock and Hegarty 2010). These authors also showed that a 10% increase in weaning percentage reduced emission intensity (kg CO2-equivalents per kg liveweight sold) by 3–4% but made little difference to the total methane emission of the enterprise. Changing lambing time away from the economic optimum did not reduce emissions intensity.

The simulations of Alcock and Hegarty (2010) show that changes in emissions intensity and total methane output arising from altered management will be modest if the total amount of feed consumed on a property remains unchanged. Producers should decide whether their management strategies will target minimising emissions intensity, which would be appropriate if a production quota were to be introduced for the enterprise. Alternately, targeting to reduce total emissions would be appropriate if an emission cap (or maximum emissions limit) were to be introduced, or the target could be a desired level of profit. Existing management options are sufficient to enable any of these goals to be achieved individually, but not simultaneously. This is evident in a GrassGro simulation of responses in emissions, productivity and profitability of a 100-ha sheep enterprise to increasing use of improved pasture (Alcock and Hegarty 2006), summarised in Table 1. The following trends are evident from Table 1.

- In the unimproved state, in which the entire property consisted of unimproved pasture, 5.28 t of enteric methane was produced per year.
- When one-quarter of the property (24 ha) consisted of improved pastures, which were stocked at a higher rate than the unimproved pastures, profit was unchanged but methane output was reduced from 5.28 t per year to 2.95 t per year while sparing three-quarters of the land area from grazing and generating the same total profit.


**Table 1.** Whole-farm methane emissions for a 100 ha property for the following scenarios: unimproved (3.5 ewes/ha), 24 ha planted with improved pastures (9 ewes/ha) or 43 ha planted with improved pastures (9 ewes/ha)

<table>
<thead>
<tr>
<th>Enterprise area (total number of ewes)</th>
<th>Profit ($/ha)</th>
<th>Methane (t/year)</th>
<th>Ungrazed land (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 ha unimproved (350)</td>
<td>70</td>
<td>5.28</td>
<td>0</td>
</tr>
<tr>
<td>24 ha improved pastures (216)</td>
<td>70</td>
<td>2.95</td>
<td>76</td>
</tr>
<tr>
<td>43 ha improved pastures (387)</td>
<td>150</td>
<td>5.28</td>
<td>57</td>
</tr>
</tbody>
</table>

- When almost half the property (43 ha) consisted of improved pastures, which were stocked at a higher rate than the unimproved pastures, methane output was the same as when one-quarter of the property consisted of improved pastures (5.28 t per year) but half of the land area was spared from grazing and profit was more than doubled ($150/ha).
- As the scenario in which 43 ha consisted of improved pastures returned more than twice the profit per unit emission than the unimproved scenario, the former would be in a stronger financial position than the latter if an emission penalty were to be imposed. Thus, emission penalties are likely to favour more intensive ruminant livestock production systems.

**Discussion**

The Australian sheep industry is based on extensive grazing for wool production and slaughter lambs, with only 14% of lambs receiving any grain finishing in 2007 (VDPI 2007). Consequently, opportunities for reducing enteric methane emissions from individual sheep are limited to changing the diet through improved pasture base, short periods of supplementation or changing the rumen ecology of the animals themselves.

Currently 87% of Australia’s land managed by agricultural business is used for grazing, while only 18% of this grazing area is improved pasture (ABS 2009). While modelling of pasture improvement has shown its potential for Australian producers to achieve reduced enteric emissions, as well as increased profitability (Alcock and Hegarty 2006), a key determinant of the financial benefit of pasture improvement has been establishment cost (Thompson 2005) and pasture replacement rates have been low. Consequently, a change in the economics of pasture improvement, due to a change in the balance of input and product values or introduction of a carbon penalty for enteric emission, will be required to further stimulate pasture improvement. Based on small-scale trials, potential pastures with a low methane yield may include leguminous pastures, especially those such as sula with appropriate CT content (Woodward et al. 2004), and pastures bred for a high oil content (Cosgrove et al. 2008) but there is insufficient data to make specific recommendations or to justify species selection on this basis. Modelling studies however had clearly demonstrated for both cattle and sheep that how the herd or flock is managed on the existing pasture can make substantial differences to emissions/unit product.

The whole-farm models of Cruickshank et al. (2009) and Alcock and Hegarty (2010) are consistent in showing that flock management to maximise animal productivity (output/unit time per head) can reduce emissions/unit product. For the self-replacing flock these include mating ewes as lambs (~7 months of age) rather than at 19 months, using improved nutrition or animal genetics to increase progeny/ewe and delaying culling of ewes by 1 year. All these manipulations assume that the feed base is unchanged and sheep numbers are modified to ensure a similar proportion of pasture grown is consumed, so a similar total enterprise emission will result. For both lamb-finishing operations and breeding enterprises, an increased plane of nutrition can further reduce emissions intensity by reducing time to slaughter. In breeding systems this allows more breeding ewes to be carried.

While the advantage of ewes chosen for higher fecundity has been addressed, the advantages of selecting for feed use efficiency are not so certain. Alcock and Hegarthy’s (2010) GrassGro farm system model assumed that because feed availability was often below ad libitum when grazing, more feed-efficient ewes would grow more on the feed available, having flow-on effects of improved reproductive performance so less breeding ewes could be run on the same feed supply. This is contrary to a superficial assessment that if efficient livestock required less feed per unit gain, then more of the fed-efficient livestock could be grazed on a pasture. Studies of the lifetime performance of feed-efficient breeding sheep are required as have been commenced for beef cattle (Jones et al. 2010). The potential for breeding for a methane trait specifically will require confirmation of the heritability of that trait and its correlation with production traits.

**Conclusions**

Ruminant livestock make a significant contribution to GHG emissions in Australia. Daily methane emissions from individual animals are strongly and predictably affected by the quantity and digestibility of feed consumed. In the absence of rumen-modifying agents, the quantity of methane arising from a sheep enterprise closely reflects the quantity and digestibility of the feed normally consumed by grazing sheep. Currently, few of the nutritional technologies available for reducing DMP are economic. The development and implementation of such technologies in the future will depend on the balance between carbon penalties or subsidies and the cost of the technology. New GHG-mitigation technologies should be evaluated in terms of their effects on whole-enterprise emissions, not just on their effects on individual animals. Management strategies that are effective in reducing emissions intensity at the level of the individual sheep (e.g. first mating of ewes as lambs) may be less effective in reducing emissions intensity at the enterprise level if stocking rates are modified to accommodate the associated change in feed consumption. Reduction of whole-farm total enteric emissions is possible, but this would require a shift to a more intensive grazing system and reallocation of a portion of grazing land to alternate uses.
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