***Jointly achieving profitability and environmental outcomes: methane abatement from genetic improvement in the Australian beef industry*[1]**

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Abstract

Selection of cattle with greater feed efficiency is known to be profitable. Savings in southern Australian beef production systems of $6.55 per breeding cow per year have been estimated for selection for lower residual feed intake (RFI), and an additional saving of $4.34 per breeding cow per year may be achieved in feedlots. Greater feed efficiency is also expected to reduce methane emissions. A gene flow model was developed to simulate the spread of improved RFI genes through both a single herd in southern Australia and in the national herd, from 2002 to 2026. Based on the estimated gene flow, voluntary feed intakes were revised annually, and changes in subsequent methane emissions were calculated for both the individual and national herd. The annual methane emissions in year 25 of selection were 15.9% less than in year one for an adopting herd. For the national herd, given differential lags in and limits to adoption for Northern and Southern Australia, the cumulative reduction in national emissions was 568.1 Gg of methane over 25 years (11.93 Mt CO_2 equivalents), with annual emissions in year 25 being 3.1% lower than in year 1. It is concluded that selection for reduced RFI will lead to substantial and lasting methane abatement while also providing savings in feed-related costs for Australian beef producers, largely as a consequence of its implementation as a breeding objective for the beef herd.

Additional keywords: residual feed intake, feed efficiency, beef industry, greenhouse gas

Introduction

The Australian agricultural sector accounted for 97.3 Mt of CO_2 equivalents (CO_2 –e) or 18 % of net national greenhouse gas (GHG) emissions in 2003, predominantly as methane (CH_4) and nitrous oxide (N_2O). The livestock sector was responsible for the majority of these net emissions (66.1 Mt CO_2 –e or 12 % of net national emissions), with the primary source being enteric fermentation resulting in the formation of methane during the digestion of feed from ruminant and some non-ruminant domestic livestock. Beef cattle produced some 63 % of the net GHG emissions derived from the livestock industries collectively (AGO 2005); and 96.5 % was from beef cattle on pasture with only 3.5 % from feedlots.

An area of debate in relation to GHG abatement strategies has focused upon land use change and forestry projects as a means GHG mitigation and incorporated into various carbon trading frameworks (Cacho, Wise and MacDicken 2004). A limitation of these carbon mitigation strategies is that they are temporary, as CO_2 captured for example by forestry growth can be released upon harvest or in the event of fire. In contrast GHG abatement strategies employed in the energy sector are permanent because an avoided emission will never reach the atmosphere (Cacho, Hean and Wise 2003). Reductions in livestock methane emissions through breeding are similar to technological improvements in the energy sector in the sense that they affect sources of GHGs rather than sinks.

Enteric methane production in the digestive tract of ruminants is a central process in the disposal of rumen hydrogen (Hegarty and Gerdes 1999) but it constitutes both a loss of digested energy and a major source of agricultural greenhouse gas (GHG) emissions[2]. The role of feed intake is recognised in most algorithms predicting methane production rate (MPR) (Blaxter and Clapperton 1965; Pelchen and Peters 1998), yet altering feed intake to reduce MPR has received little attention due to concern over correlated reduction in animal production. Genetic variation in feed intake exists, independent of liveweight (LW) or average daily gain (ADG), and this variation provides a basis for genetic selection for feed-use efficiency of cattle (Arthur *et al*. 2001*a*). Cattle that eat less than their peers for equivalent LW and ADG have a low

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[2] Methane has 21 times the global warming potential of CO_2.

residual feed intake (RFI) and are more feed efficient as shown by lines of cattle divergently selected for RFI (Arthur *et al*. 1996).

Selection for cattle with low RFI has been found to be profitable in southern Australian beef production systems. Griffith *et al.* (2004) reported an on-farm benefit of the RFI technology of $6.55 per breeding cow per year. An additional benefit based upon savings achieved in feedlots as a consequence of breeding for low RFI cattle was estimated at $4.34 per breeding cow per year (Griffith *et al*. 2004).

This study uses the herd structure and methodologies of the National Greenhouse Gas Inventory (NGGI; AGO, 2004*a*) to model the methane abatement resulting from the anticipated adoption of RFI in breeding programs within the Australian beef industry over the next 25 years. In addition the value of these estimated savings in GHG are valued using prescribed penalty GHG rates for NSW industries.

Methodology

A four-step procedure was used to model the effect of the reduced RFI on enteric methane emissions.

1. Develop a RFI gene flow model for a representative commercial beef herd.
2. Derive from the gene flow model the expected annual change in feed intake for each age and sex cohort of beef animals over a 25-year planning horizon, consistent with those beef animal categories used in the 2002 NGGI (AGO 2004*a*).
3. Use these predicted changes in annual feed intake to determine the dry matter (DM) intake requirement of different classes of beef animals for maintenance and for LW gain in the subsequent year, and apply these values to the AGO (2004*a*) methodology for calculating enteric methane production.
4. Multiply the discounted methane production levels by beef cattle numbers to determine annual aggregate methane production for the beef industry over the 25-year planning horizon.

These steps were initially used to model feed intake and MPR in a single beef herd in southern Australia selecting for RFI, and then in the Australian national herd where only some cattle were selected for RFI. In the latter analysis, lagged and differential adoption levels of selection for improved RFI by Northern and Southern Australian beef herds (including cattle in feedlots) were assumed. Calculated values were then compared to the base level of 2002 methane output. The analysis was implemented using Matlab Version 7.0 (Mathworks Inc. 2004). The gene flow and feed intake models are detailed in the Appendices.

A number of biological and management assumptions were necessary to model the impact of the RFI technology at the farm. Following Exton *et al*. (2000), it was assumed that beef producers could initially purchase bulls with EBVs for RFI that were 4 % better than average bulls in the Australian herd. An annual improvement in RFI of the seedstock herd of 0.16 kg DM/day appears to be feasible (Arthur *et al*. 2001*b*); however, given the likelihood that multi-trait breeding objectives will be pursued by the industry, the rate of progress in RFI was assumed to be half of the potential (0.08 kg DM/day) following Exton *et al*. (2000). In the study by Arthur *et al*. (2001*b*), daily feed intake averaged 10.5 kg DM/day for cattle that had not been selected for the RFI trait. Therefore, a reduction in RFI of 0.08 kg DM/day is equivalent to a 0.76 % improvement in RFI per year.

Individual Herd

In the first instance, the gene flow model was applied to an individual 100-cow commercial beef herd. This herd was assumed to be a self-replacing cow-calf enterprise producing heavy feeder steers. Cows were joined to calve in August and September, and heifers were joined to calve at 2 years of age. Heifers were sold as weaners at around 9 months of age, while steers were sold at approximately 18 months of age at 440-450 kg LW. Herd parameters including mortality and cull rates are provided in Alford *et al*. (2004) and are consistent with the cow-herd model described in the gene flow model. Assumptions regarding average seasonal LW, ADG and seasonal DM digestibility of feed intake were the values applied in the NGGI (AGO 2004*a*) for New South Wales.

A 25-year planning period was used in this study, as in similar investigations examining RFI (eg., Archer and Barwick 1999; Exton *et al*. 2000). This is also consistent with the timeframe commonly used by geneticists to evaluate beef-cattle breeding programs, for example Nitter *et al*. (1994). The DM-intake estimates of the 100-cow beef herd were adjusted for each class of beef animal and the total annual production of methane was determined for each year of the planning horizon.

National herd

The same methodology was applied to the national herd numbers detailed in the NGGI (AGO 2004*b*). However, various adoption rates and adoption time lags were applied as detailed below. The extensive nature and generally lower fertility rates of the Northern beef herd (O'Rourke *et al*. 1990) reduces the potential rate of genetic gain possible. Factors such as extended mating and calving periods (Davis 1993) lead to lower annual rates of genetic improvement. Consequently, it was assumed that the rate of genetic improvement in the Northern beef herd for RFI (0.38 % per annum) was half the annual gain achieved by the Southern herd (0.76 % per annum). Since the 2002 NGGI (AGO 2004*b*) aggregates cows greater than 2-years old into one category, the discount to DM-intake applied to this category was a weighted average of the cow-age cohorts obtained from the gene flow model (refer to Appendix 1).

Adoption rates

Figure 1 illustrates the assumed trend in adoption of genetic improvement in NFI for the Southern and Northern beef herds. The base adoption rate assumed for the trait by the Australian beef industry was zero in 2002, and the maximum adoption level was 30 % for all cattle, consistent with that used by Griffith *et al*. (2004). This maximum is attained by year 11. The start year, 2002, is the first year that an EBV for RFI was published for Angus and Hereford-Poll Hereford breeds in Australia (Arthur *et al*. 2004).

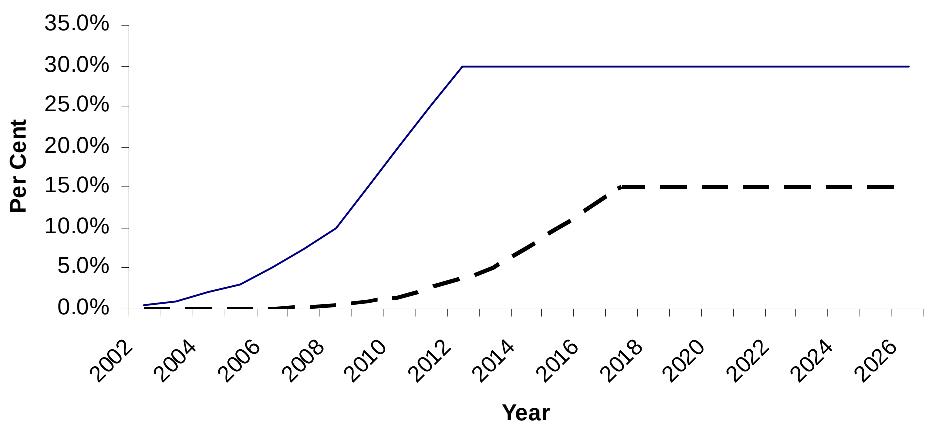

Figure 1. Assumed adoption rate (as a percentage of cattle numbers) of genetic improvement of RFI in Southern (____) and Northern (▬ ▬) Australian beef herds

For the Northern herd in Australia, it was assumed that adoption would lag the base adoption rate by 5 years (Farquharson *et al.* 2003) and that the maximum adoption level would be only half that achieved in the Southern herd. In 2002, an estimated 80.1 % of the Northern herd contained some level of Brahman or other tropical breed genetics (Riley *et al*. 2001), and while RFI has been examined in tropically-adapted breeds (Arthur *et al*. 2004), commercial application has occurred mostly in the Southern beef herd (Exton *et al*. 2000). Further, the overall benefit of the trait in the Northern beef herd may be of less potential significance because of lower overall feed costs per unit of turnoff (Barwick *et al*. 2003).

Results and Discussion

Response in an adopting herd

For the representative 100-cow commercial herd in Southern Australia, which purchased bulls superior for RFI in year 1, the cumulative total of enteric methane abated over the 25-year simulation period was 0.0245 Gg. This represents a 7.4 % cumulative decrease in enteric methane production over the simulation period, compared to an unimproved herd. As seen in Table 1, by year 25 following adoption of the RFI trait, the reduction in RFI in a commercial herd in southern Australia ranges from 11.22 % to 21.48 % for the various classes of beef cattle.

Table 1. Gene flow of percentage RFI reduction for different age cohorts in a representative commercial herd over 25 years (expressed as % change in RFI over Year 0)

			Cow age cohorts								
Year	**< 1 y.o.***	**1 y.o. to 2 y.o.**	**2 y.o.**	**3 y.o.**	**4 y.o.**	**5 y.o.**	**6 y.o.**	**7 y.o.**	**8 y.o.**	**9 y.o.**	**Bulls**
1	0.67	0	0	0	0	0	0	0	0	0	1.33
2	1.46	0.67	0	0	0	0	0	0	0	0	2.92
3	2.45	1.46	0.67	0	0	0	0	0	0	0	4.76
4	2.96	2.45	1.46	0.67	0	0	0	0	0	0	5.52
5	3.56	2.96	2.45	1.46	0.67	0	0	0	0	0	6.28
6	4.17	3.56	2.96	2.45	1.46	0.67	0	0	0	0	7.04
7	4.82	4.17	3.56	2.96	2.45	1.46	0.67	0	0	0	7.80
8	5.48	4.82	4.17	3.56	2.96	2.45	1.46	0.67	0	0	8.56
9	6.17	5.48	4.82	4.17	3.56	2.96	2.45	1.46	0.67	0	9.32
10	6.89	6.17	5.48	4.82	4.17	3.56	2.96	2.45	1.46	0.67	10.08
11	7.61	6.89	6.17	5.48	4.82	4.17	3.56	2.96	2.45	1.46	10.84
12	8.33	7.61	6.89	6.17	5.48	4.82	4.17	3.56	2.96	2.45	11.60
13	9.04	8.33	7.61	6.89	6.17	5.48	4.82	4.17	3.56	2.96	12.36
14	9.76	9.04	8.33	7.61	6.89	6.17	5.48	4.82	4.17	3.56	13.12
15	10.49	9.76	9.04	8.33	7.61	6.89	6.17	5.48	4.82	4.17	13.88
16	11.22	10.49	9.76	9.04	8.33	7.61	6.89	6.17	5.48	4.82	14.64
17	11.96	11.22	10.49	9.76	9.04	8.33	7.61	6.89	6.17	5.48	15.40
18	12.70	11.96	11.22	10.49	9.76	9.04	8.33	7.61	6.89	6.17	16.16
19	13.44	12.70	11.96	11.22	10.49	9.76	9.04	8.33	7.61	6.89	16.92
20	14.18	13.44	12.70	11.96	11.22	10.49	9.76	9.04	8.33	7.61	17.68
21	14.93	14.18	13.44	12.70	11.96	11.22	10.49	9.76	9.04	8.33	18.44
22	15.68	14.93	14.18	13.44	12.70	11.96	11.22	10.49	9.76	9.04	19.20
23	16.43	15.68	14.93	14.18	13.44	12.70	11.96	11.22	10.49	9.76	19.96
24	17.18	16.43	15.68	14.93	14.18	13.44	12.70	11.96	11.22	10.49	20.72
25	17.93	17.18	16.43	15.68	14.93	14.18	13.44	12.70	11.96	11.22	21.48

* y.o = years old

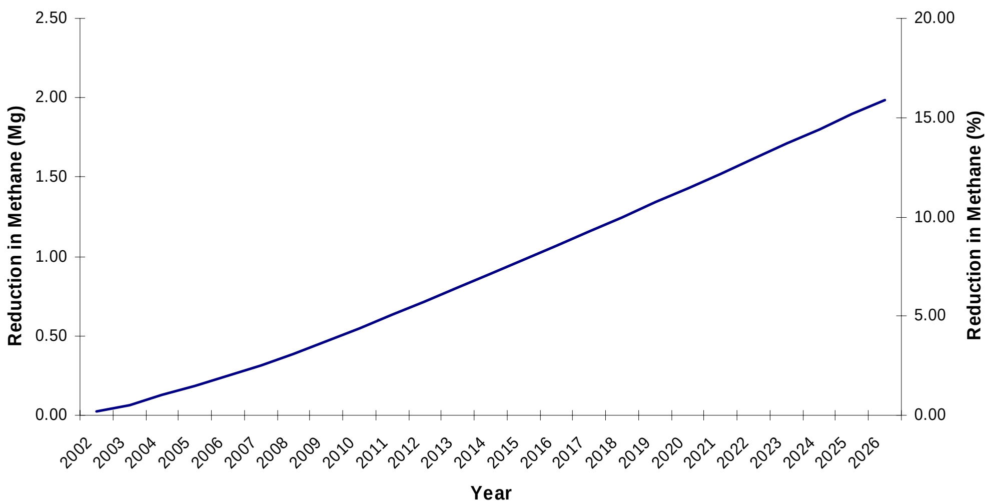

Figure 2. Estimated annual reduction in enteric methane produced by a representative 100-head commercial cow herd in Southern Australia as a result of selection of bulls using an index providing lower RFI over the period 2002 to 2026

Figure 2 shows that the annual saving in methane production over an unimproved herd by year 25 was 15.9 % across the whole herd. This analysis represents the potential enteric methane abatement for a commercial herd that uses the RFI superior bulls from year 1.

The continuous reduction in RFI and enteric methane production modelled here is supported by findings from research into feed efficiency carried out in other species, indicating that there is substantial genetic variation for RFI in animal populations. For example, Hughes and Pitchford (2004) found a significant and symmetrical response to selection for RFI in mice over 11 generations. These findings were consistent with other researchers (Bünger *et al*. 1998; Nielsen *et al*. 1997), where selection for feed efficiency traits (corrected for body weight) resulted in linear responses for up to 38 generations examined. This indicates that there is substantial genetic variation for the trait, which is unlikely to be exhausted within the period considered in this study.

Response in the national herd

Reductions in enteric methane production of the entire Australian beef herd, incorporating the patterns of adoption shown in Figure 1, would result in a cumulative total of 568.1 Gg of methane abated over a 25-year period. In the final year of the simulation period, the annual saving in enteric-methane production from the Australian beef industry was 60.9 Gg or 3.1 % of the 2002 inventory total of 1964.8 Gg.

Sensitivity to model assumptions

Benefits relating to methane abatement from reduced RFI might be enhanced by increasing the annual rate of genetic gain and/or by increasing the level of adoption of the RFI technology by Australian beef producers. Table 2 shows the impact on the base results of an increase in the assumed level of adoption or in the annual rate of genetic gain.

In relation to increasing the annual rate of genetic gain, currently the identification of superior animals for RFI is undertaken by conducting relatively expensive feed-intake trials on individual animals (Graser 2004). Alternate methods of identifying animals that are genetically superior for RFI, such as the use of indirect markers such as insulin-like growth factor-I (IGF-I), may decrease this cost (Moore *et al*. 2005). Using IGF-I to indirectly select for RFI is quicker, cheaper and can be applied to younger animals. This allows breeders to make selection decisions earlier and may possibly increase the number of animals measured for feed intake, thus increasing the potential of identifying genetically superior animals (Moore *et al*. 2005). A 50 % increase in the annual rate of genetic improvement in RFI for bulls used in the commercial herd, from 0.76 % to 1.14 % per year, would result in a decrease in annual enteric methane production of 84.4 Gg, or 4.3 % by year 2026 (year 25 of the simulation).

Table 2. Sensitivity of final year enteric methane savings to assumed adoption rates of genetic gain in the Australian herd

	Annual methane abated	
	Gg/year 25 (CO_2-e)	% improvement over base scenario
Base scenario (0.76 % annual rate of genetic improvement and 30 % maximum adoption)	60.9 (1.28 Mt)	n.a.
50 % increase in maximum adoption rates	91.3 (1.92 Mt)	50.0
50 % increase in annual rate of genetic gain	84.4 (1.77 Mt)	38.6

In relation to increasing the rate of adoption and/or raising the maximum adoption level of RFI improvement, especially in the Northern herd, the new Cooperative Research Centre for Beef Genetic Technologies (Beef CRC) has an objective to increase adoption rates for RFI technologies (Beef CRC 2004). A 50 % increase in the maximum level of adoption of the RFI technology to 45 % and 22.5 % for the Southern and Northern beef industries respectively, would result in an increase in annual abatement of enteric methane to 91.3 Gg or 4.7 % by year 25. This analysis provides a measure of the potential benefits of the Beef CRC's goal of enhancing adoption of RFI technologies.

While breeding for lower RFI will result in decreases in enteric methane produced by the Australian beef industry, the long generation intervals associated with cattle-breeding programs mean that the technology should be considered as a longer-term strategy for methane abatement. It is evident from Figure 3 that there will be limited abatement from the implementation of the RFI technology in the first commitment period of the Kyoto Protocol (2008-2012). In 2008, only 1.8 Gg, or 0.1 % of enteric methane would be abated over the 2002 inventory year. By 2012, 10.7 Gg of enteric methane would be abated, or 0.5 %, relative to the 2002 inventory.

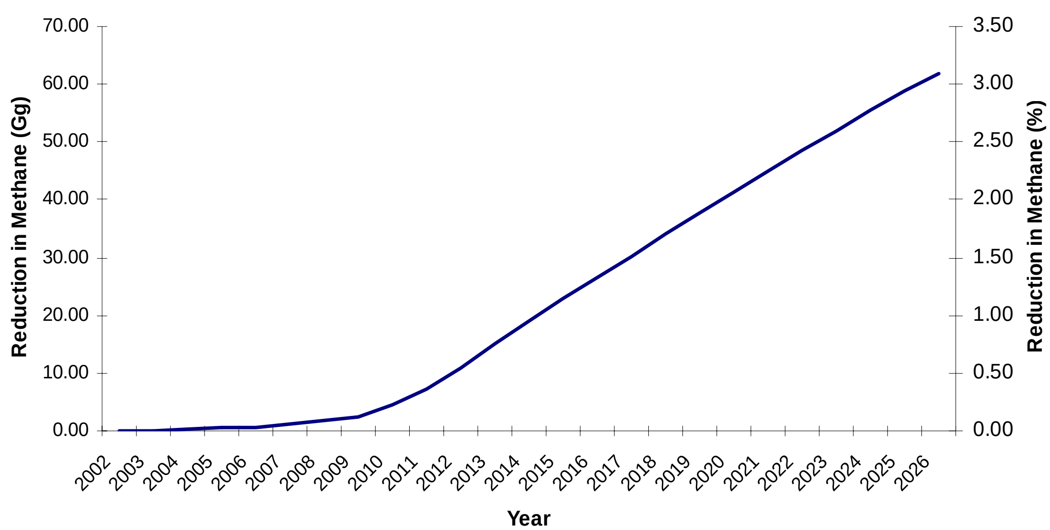

Figure 3. Estimated annual reduction in enteric methane produced by the Australian beef herd as a result of reduced RFI over the period 2002 to 2026

The simulation assumes that the cattle population remains constant and equal to the 2002 beef-cattle population. The Australian beef-cattle herd has decreased slightly from 24,739 million in 2002 to 24,110 million head in 2004 (provisional, ABS 2004). Australian beef-cattle numbers are typically cyclical, and are influenced by the US cattle cycle (Griffith and Alford 2002). However, since 1984 the Australian herd has increased at an average annual rate of 1.15 %, although prior to this period it reached a record 29.833 million head in 1976.   Another important factor is the increase in the size of the Northern herd relative to the Southern herd. This is partly a consequence of increased productivity amongst Northern beef producers (Gleeson *et al*. 2003). Given the assumed difference in adoption and the potential impact of reduced RFI on Northern and Southern herds, any continuing regional shift in beef-cattle numbers will impact on predicted emissions from the industry.

While the current assessment has only considered abatement of methane, reduced RFI would also reduce the intake of dietary nitrogen and hence potential nitrous oxide (N_2O) release from manure. Although Australia's dry environment and extensive grazing practices mean that overall (N_2O) emissions from manure are relatively modest, in moister environments and locations where pastures are nitrogen fertilised abatement of N_2O could also be a substantial benefit from improved RFI.

Benefits of RFI technology compared with Forestry activities

In contrast to the permanent nature of the GHG abatement achieved from genetic selection for low RFI in beef cattle, carbon sequestration using forestry programs is largely temporary since when forests are harvested CO_2 is released. This can lead to complex and expensive monitoring costs when forestry projects are used as GHG mitigation programs (Cacho *et al*. 2003).

One tonne of carbon in wood is equivalent to 3.67t CO_2-e and 1 hectare of growing forest may capture approximately 10t CO_2/ha/yr (Cacho *et al*. 2003). Therefore assuming the base scenario for the rate of adoption of the RFI trait in the Australian beef herd, the annual amount of methane abated by year 25 (1.28Mt CO_2-e, Table 2) is equivalent to an area of approximately 128,000 ha of forest. This forestry area is equivalent to 7.5 % of the total area of plantation forest in Australia in 2005, with an annual increase in the area planted to timber averaging some 75,000 ha nationally for the 5 years to 2005 (National Forest Inventory, 2005). A question for further investigation is how beef producers might access any economic benefit accruing under a carbon trading market as a consequence of breeding for low RFI cattle.

In the meantime it is possible to estimate an economic value for this reduction in methane emissions from the Australian beef herd. The estimated 568.1 Gg of methane saved over the 25 year period is equivalent to 11.93 Mt CO_2-e, or about 477,000 tonnes of CO_2-e per year. According to the NSW Independent Pricing and Regulatory Tribunal (2005), under the NSW Greenhouse Abatement Scheme the current penalty for NSW power generators exceeding their target level of CO_2 emissions is $10.50 per tonne CO_2. Thus a minimum value for the saved methane output due to the adoption of RFI genetics in the national beef herd is $5 million per year on average. In more mature carbon markets such as in Europe, the price has exceeded 20 Euros per tonne. At this price at current exchange rates, the value of the reduction in methane emissions due to the adoption of NFE could be as high as $15 million per year across the national herd.

Alternative methane abatement strategies

As an existing technology, livestock selection for reduced RFI is one of the few readily implementable strategies for reducing methane emissions from the beef industry that does not require a concomitant reduction in livestock numbers or level of individual-animal production. Improvement of pasture digestibility will generally reduce the methane cost of beef production (methane/kg of beef), but increase the daily (or annual) methane emission by the individual, due to the rise in feed intake associated with improved digestibility of pasture (Freer and Jones 1984; Hegarty 2001). There are few rumen modification strategies available to the beef industry to reduce methane production. The ionophore Monensin™ is one available technology that reduces methane production, partly by reducing feed intake and partly by altering rumen-hydrogen partitioning. While early studies suggested Monensin's abatement effect was short lived, recent studies have shown a longer-term impact (Johnson *et al*. 1994; Mbanzamihigo *et al*. 1996). Feed additives that inhibit methane production are being considered (McCrabb *et al*. 1997), but since these are likely to require ongoing inclusion on a daily basis, they may only be suited to feedlot cattle, which contribute only 3.5 % of methane emissions from the Australian beef herd. It can be expected that reductions in enteric methane production due to reduced RFI will be additive to abatement delivered by technologies modifying rumen fermentation.

Conclusions

Selection for reduced RFI is expected to reduce greenhouse-gas emissions from beef cattle, although the time lag for abatement is substantial. Selection for reduced RFI also has been shown to be a profitable technology (Griffith *et al*. 2004) for Southern Australian beef producers, as a result of the herd's improved feed efficiency. Therefore, enteric methane abatement resulting from selection for lower RFI is not at the cost of farm profit, as may be the case for some alternate abatement strategies. Profitability and environmental outcomes may be jointly achieved.

RFI offers a commercially attractive and practical abatement technology because it does not demand reductions in livestock numbers or level of production. The two particular aspects of selection for improved RFI that ensure its role in livestock greenhouse-gas abatement are (1) the impact of the genetic improvement on the grazing herd, not just finishing animals, and (2) the cumulative nature of the response over time.

In contrast to the temporary nature of GHG abatement achieved through forestry projects, selection for beef cattle with low RFI confers permanent methane reductions. Policy issues for consideration include whether the permanent abatement that is achieved through the genetic improvement in Australia's beef cattle herd be recognised and accounted for in the national emissions inventory and whether the beef industry may be able to capture any economic benefits that could accrue under a carbon market scheme.

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Appendix 1- *The Gene Flow Model*

The accumulated improvement in RFI was determined by developing a gene flow model based upon fixed proportions of the age cohorts within a representative commercial cow herd, with bulls purchased from the seedstock sector. Other biological and technical parameters concerning herd dynamics were generally consistent with the gene flow model for Australian beef cattle developed by Nitter *et al*. (1994). It was assumed that no additional selection pressure for RFI occurred in commercial herds, with replacement heifers selected on traits that were independent of RFI.

The commercial female herd consisted of ten age groups (m = 0,1,…,9) representing heifer calves (less than 1 year-old), yearling heifers (1-2 year-old), 2 year-old heifers and cows up to 9-years old. Bulls were sourced from seedstock herds at 3 years of age and used in the commercial herd for 3 years at a joining rate of 3 %. The cow herd in steady state was composed of a given proportion of animals in each age group, denoted by a vector **p** with elements p_m, satisfying the constraints:

$$0 < p_m < 1$$

and

$$\sum_{m=2}^{9} p_m = 1$$

The values of **p** are 0.198, 0.171, 0.147, 0.127, 0.110, 0.095, 0.082 and 0.070 for ages 2 to 9 respectively.

The improvement in RFI ($C_{t,m}$) achieved by a given age cohort (m) in the commercial herd during year t was calculated based on the number of improved animals available the previous year:

$$C_{t,m} = C_{t-1,m-1}; \text{ for } m = 1,\dots,9. \quad (1)$$

The improvement in RFI was introduced through the calves as

$$C_{t,0} = \sum_{m=2}^{9} p_m \frac{C_{t,m} + B_t}{2} \quad (2)$$

B_t represents the average savings in feed intake of the existing seedstock herd:

$$B_t = \frac{\sum_{n=1}^{3} S_{t,n}}{3} \quad (3)$$

where $S_{t,n}$ represents the improvement in RFI by bull age n in year t in the seedstock herd, and each bull is used in the herd for 3 years.

The RFI of older bulls depends upon the level of the trait in previous years:

$$S_{t,n} = S_{t-1,n-1};\ \text{for } n = 2,3 \text{ and } t > 1. \qquad (4)$$

The new bulls (of age 1 year) have an average RFI determined by:

$$S_{t,n} = S_{t-1,1} + \delta_g;\ \text{for } t > 1, \qquad (5)$$

where δ_g is the percentage annual improvement in the average EBV for RFI.

It is acknowledged that differences in biological and technical parameters exist between the Northern and Southern Australian systems which influence potential rates of genetic gain. However, several differing population parameters have contrary effects on the potential rate of genetic gain in the Northern and Southern herds respectively. For example, the average age at first calving is higher in the Northern herd than that applied in this model, which would slow genetic progress. However, a shorter average productive lifetime in the Northern cow herd compared to a Southern herd would have the opposite effect by increasing the possible rate of genetic gain. Further, given the limited knowledge of RFI with respect to its correlation with other beef production traits, a single representative gene flow model was assumed to be adequate across all of the Australian herd.

This gene flow model represented by setting $S_{1,1} = 4.0\%$ and $S_{1,2} = S_{1,3} = 0$ and then solving equations (1) to (5) iteratively through time for 25 years, from 2002 to 2026. Sensitivity analysis on the likely improvement in RFI EBV for the commercial herd was undertaken by changing the values of the initial improvement.

Solution of the model results in a matrix of predicted reductions in DM-intake for the commercial herd, measured relative to the base situation (2002 NGGI year). Table 1 shows the matrix **C**, for which elements are $C_{t,m}$. Matrix **C** has 25 rows and 10 columns, which represent the simulation years and age groups of females in the herd respectively. Male offspring were assumed to have the same phenotype for RFI, as females of the same age. That is, male calves have a predicted reduction in DM-intake of $C_{t,0}$. Male (steer) offspring older than 1 year (AGO 2004*b*) were assumed to have a reduction in RFI equivalent to the average of $C_{t,1}$ and $C_{t,2}$, to account for steers kept for longer than 2 years.

Applying the geneflow model to the national herd requires an assumption regarding the beef cow population since the 2002 NGGI (AGO 2004*b*) pools cows greater than 2-years old into one category, the discount to DM-intake applied to this category was a weighted average improvement of RFI of the cow-age cohorts obtained from the gene flow model (refer to Appendix 1). That is, in any year *t*, the discount applied to the DM-intake to the annual number of cows greater than 2-years old is:

$$\text{RFI Cows } (>2\text{y.o.})_t = \sum_{m=2}^{9} p_m C_{t,m} \qquad (15)$$

Appendix 2 - *Feed Intake Model*

The predicted changes in NFI of different classes of beef animals were applied to the NGGI for maintenance and for LW gain using the methodology developed by the AGO (2004*a*) to derive the adjusted total enteric methane production from beef cattle. That is, the DM-intake (I_{ijkl} kg DM/head/day) of cattle is determined from liveweight (*W*) and liveweight gain (*LWG*) for each state (*i*), region (*j*), season (*k*) and age and class of beef animal (*l*) and adjusted for changes in NFI for each class of animal for each year ($C_{t,m}$):

$$I_{ijklt} = \left(\left(1.185 + 0.00454W_{ijkl} - 0.0000026W_{ijkl}^2 + 0.315LWG_{ijkl}\right)^2 * MA_{ijkl=5}\right) * \left(1 - C_{t,m}\right) \quad (6)$$

where $MA_{ijkl=5}$ is the additional intake for milk production (Minson and McDonald 1987), given by:

$$MA_{ijkl=5} = \left(LC_{ijkl=5}.FA_{ijkl=5}\right) + \left(\left(1 - LC_{ijkl=5}\right).l\right) . \quad (7)$$

$LC_{ijkl=5}$ is the proportion of cows over 2 years of age lactating (*l*= 5) and $FA_{ijkl=5}$ is a feed intake adjustment for calving cows (AGO 2004*a*).This DM-intake is converted to gross energy intake (*GEI*), assuming that feed dry matter has, on average, a gross energy intake of 18.4 MJ/kg (SCA 1990, AGO 2004*a*):

$$GEI_{ijklt} = 18.4I_{ijklt} . \quad (8)$$

The DM-intake relative to that needed for maintenance $\left(L_{ijklt}\right)$ was estimated as actual intake divided by DM-intake for maintenance of a non-lactating animal with no weight gain (AGO 2004*a*):

$$L_{ijklt} = I_{ijklt} / \left(1.185 + 0.00454W_{ijkl} - 0.0000026W_{ijkl}^2\right)^2 \quad (9)$$

From this, the percentage of the gross energy intake that is yielded as methane was derived to finally determine total enteric methane production:

$$Y_{ijklt} = 1.3 + 0.112DMD_{ijkl} + L_{ijklt}\left(2.37 - 0.05DMD_{ijkl}\right) \quad (10)$$

where, DMD_{ijkl} is the digestibility of feed (%) as detailed by AGO (2004*b*). Then total daily production of methane (M_{ijklt} , kg CH_4/head/day) was calculated as:

$$M_{ijklt} = \left(Y_{ijklt} / 100\right)GEI_{ijklt} / F \quad (11)$$

for temperate regions of Australia, where *F* represents the energy per kg of methane (55.22 MJ/kg CH_4). For cattle on tropical pastures, total daily methane production is given by (Kurihara *et al*. 1999, AGO 2004*a*):

$$M_{ijklt} = \left(41.5 I_{ijklt} - 36.2\right) / 1000 \tag{12}$$

Total annual enteric methane production was then derived for each region, state, season and beef animal class as identified by NGGI, by multiplying by the number of cattle and summing to estimate a national annual estimate of enteric methane production (AGO 2004*a*).

For feedlot cattle, the NGGI uses methane emissions equations developed by Moe and Tyrrell (1979), which predicts daily enteric methane yield (Y_{ij}, MJ CH_4 /head/day) from 3 components of dietary carbohydrate intake. These are soluble residue (SR_{ij}), hemicellulose (H_{ij}) and cellulose (Ce_{ij}), for feedlot cattle in each state (*i*) and for an average length of stay in the feedlot (*j*), which was taken to be 75, 140 or 250 days (AGO 2004*a*):

$$Y_{ij} = 3.406 + 0.51 SR_{ij} + 1.736 H_{ij} + 2.648 Ce_{ij} \tag{13}$$

Each of these carbohydrate components is determined from the total intake of the animal (adjusted by the estimated improvement in NFI, $C_{t,m}$), the estimated proportions of the diet of each class of animal that is grass, legume, grain and other concentrates and the SR_{ij}, H_{ij} and Ce_{ij} fractions of each of these components. Detailed equations, dietary assumptions and feedlot cattle numbers are provided in the NGGI methodology (AGO 2004*a*) and related appendices (AGO 2004*b*).

Total daily methane production (M_{ij}, kg CH_4/head/day) is given by (AGO, 2004*a*):

$$M_{ij} = Y_{ij} / F \tag{14}$$

where F has a value of 55.22 MJ/kg CH_4 (Brouwer 1965). Enteric methane production was then summed for all classes of feedlot cattle, across all states to derive an annual estimate of methane production. This was then added to the estimate for beef cattle on pasture.