The impact of genetic selection on greenhouse-gas emissions in Australian dairy cattle

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Abstract. In Australia, dairy cattle account for ~12% of the nation's agricultural greenhouse-gas (GHG) emissions. Genetic selection has had a positive impact, reducing GHG emissions from dairy systems mainly due to increased production per cow, which has led to (1) requiring fewer cows to produce the same amount of milk and (2) lowering emissions per unit of milk produced (emission intensity). The objective of the present study was to evaluate the consequences of previous and current genetic-selection practices on carbon emissions, using realised and predicted responses to selection for key traits that are included in the Australian national breeding objective. A farm model was used to predict the carbon dioxide equivalent (CO_2-eq) emissions per unit change of these traits, while holding all other traits constant. Estimates of the realised change in annual CO_2-eq emissions per cow over the past decade were made by multiplying predicted CO_2-eq emissions per unit change of each trait under selection by the realised rates of genetic gain in each of those traits. The total impact is estimated to be an increase of 55 kg CO_2-eq/cow.year after 10 years of selection. The same approach was applied to future CO_2-eq emissions, except predicted rates of genetic gain assumed to occur over the next decade through selection on the Balanced Performance Index (BPI) were used. For an increase of AU$100 in BPI (~10 years of genetic improvement), we predict that the increase of per cow emissions will be reduced to 37 kg CO_2-eq/cow.year. Since milk-production traits are a large part of the breeding goal, the GHG emitted per unit of milk produced will reduce as a result of improvements in efficiency and dilution of emissions per litre of milk produced at a rate estimated to be 35.7 g CO_2-eq/kg milk solids per year in the past decade and is predicted to reduce to 29.5 g CO_2-eq/kg milk solids per year after a conservative 10-year improvement in BPI (AU$100). In fact, cow numbers have decreased over the past decade and production has increased; altogether, we estimate that the net impact has been a reduction of CO_2-eq emissions of ~1.0% in total emissions from the dairy industry per year. Using two future scenarios of either keeping the number of cows or amount of product static, we predict that net GHG emissions will reduce by ~0.6%/year of total dairy emissions if milk production remains static, compared with 0.3%/year, if cow numbers remain the same and there is genetic improvement in milk-production traits.

Additional keywords: abatement, climate change, methane, nitrous oxide.

Introduction

In Australia, dairy cattle account for ~12% of the nation's 72 million tonnes per annum of carbon dioxide equivalents (CO_2-eq) from agriculture (between 2004 and 2014; DCCEE 2016*a*). Dairy production has made advances in efficiencies over the past 60 years as a result of changes in nutrition, management and breeding (Bell *et al*. 2012). However, losses of dietary energy in the form of methane (CH_4), as well as nitrogen (N) in manure, are inefficiencies and sources of GHG pollution in the form of CH_4 and nitrous oxide (N_2O) gases (FAO 2010). Given the effect of GHG emission levels on climate change, mitigation of these gases has gained importance in recent years. While diet manipulation can alter the potential production of CH_4 (Moate *et al*. 2016) and N_2O emissions, selective breeding could offer a cost-effective means of abating emissions in the medium to

long term, i.e. minimising the environmental impact and increasing the profitability of dairy systems at little to no extra cost. In addition, the effect of genetic selection is permanent and cumulative.

It is recognised that within dairy systems, the largest source of GHG emissions is from enteric fermentation and CH_4. Over 30 years (between 1980 and 2010), Moate *et al*. (2016) estimated that production of enteric CH_4 has been almost static (185 000 t in 1980 versus 182 000 t in 2010); at the same time, milk production has increased, so that the intensity of CH_4 emissions (i.e. emissions per unit of product, in this case, milk) has declined considerably by 40% from ~33.6 g CH_4/kg milk to 19.9 g CH_4/kg milk. Since milk-production traits are a large part of the breeding goal, the reduction of the GHGs emitted per unit of milk produced has been the result of improvements in

efficiency and dilution of emissions per litre of milk produced. Capper *et al.* (2009) and Wall *et al.* (2010) identified that the main reduction in GHG intensities could be attributed to improvements in production and to increased gross efficiency (i.e. the ratio of yield of milk to resource input). Increased production means that fewer animals are required to produce the same amount of product, while increased gross efficiency dilutes the maintenance costs of animals in the system.

The Australian national breeding objective, known as the Balanced Performance Index (BPI), includes traits that contribute to cow profitability, farmer preferences and desired gains (Byrne *et al.* 2016). The BPI encompasses biological traits associated with milk production, longevity, fertility, feed efficiency and health. Feed-efficiency breeding values, known as feed saved, include genomic breeding values for residual feed intake and breeding values for maintenance requirements based on predicted cow bodyweight (Pryce *et al.* 2015). Thus, by selecting for production traits and feed saved simultaneously, it is anticipated that gross efficiency will improve in Australian dairy cows (Byrne *et al.* 2016). Furthermore, Hegarty *et al.* (2007) showed that selection on residual feed intake is likely to reduce GHG emissions.

The aims of the present study were to (1) estimate the impact of selection over the past decade on GHG emissions accounting for per-cow emissions estimated from realised rates of genetic gain and a reduction in number of cows and (2) estimate future changes in GHG emissions through projected rates of genetic gain. For the second aim, we explored two scenarios, one where the national level of milk production is static and cow numbers reduce, and the other where cow numbers are static and milk production increases.

Materials and methods

GHG emissions and modelled genetic changes

Sources of GHG emissions were from enteric and manure CH_4 and direct and indirect N_2O from storage of and application of manure (DCCEE 2016b). The loss of CH_4 and N_2O emissions from livestock can be evaluated by assessing the total CO_2-eq emissions associated with production. The kilograms of CO_2-eq emissions were calculated using conversion factors from CH_4 to CO_2 and from N_2O to CO_2 of 25 and 298 respectively (IPCC 2007). Emissions were defined as CO_2-eq emissions per cow and per kilogram of milk solids.

A bio-economic model developed by Bell *et al.* (2013) was used to calculate the effect of a unit change in milk, fat, protein, liveweight, dry matter intake, somatic cell count and calving-interval traits on CO_2-eq emissions per cow and per kilogram of milk solids. Responses in each trait are quantified by calculating differences between the current state (baseline situation) and a positive or negative change in a trait (adjusted situation). The model was used in the current study to dynamically represent an Australian dairy herd and assess effects of changes in traits (average production values shown in Table 1).

There were 12 age classes (from birth to 12th parity). The age structure of the herd was in a steady-state, which was achieved using a Markov-chain approach, where the herd is described as a vector of states (Stott *et al.* 1999) and is used to calculate the replacement rate and number of cows in each age class. For each

Table 1.   Average production values for the baseline steady-state herd and an average cow in Australia, updated from Bell *et al.* (2013), used to derive changes in carbon dioxide equivalent emissions due to genetic selection in the bio-economic model

Parameter	Unit	Average herd
Age at first calving	Days	730
Number of lactations		3.0
Gestation	Days	283
Lactation length	Days	324
Calving interval	Days/lactation	401
Milk volume	kg/lactation	6528
Milk fat yield	kg/lactation	251
Milk protein yield	kg/lactation	207
Mature liveweight	kg	575
Survival	%/lactation	70.7
Dry-matter intake[A]	kg/day	15.6
Nitrogen excretion[A]	kg/day	0.34
Enteric methane[A]	g/day	322
Manure methane[A]	g/day	30
Manure nitrous oxides[A]	g/day	6

[A]Includes contribution from replacement heifer.

age class, the feed requirements and milk-production level were calculated using average farm-level milk recording data from the national dairy cow population (from the Australian Dairy Herd Improvement Scheme (ADHIS), www.ADHIS.com.au, verified 10 February 2017) and a least cost ration formulated to meet the requirements of the animal. The model assumed that energy was non-limiting and was required for production, maintenance, activity, pregnancy and growth. The feed intake was calculated from the total metabolisable energy required and the net energy supplied (Emmans 1994), assuming that a typical lactating cow diet was 68% forage and 32% cereal grain, and 100% pasture for a milking-herd replacement.

Realised rates of genetic gain for Holstein heifers born between 2004 and 2014 were estimated as the linear regression of annual means of cow breeding values (ABVs) for milk, fat and protein yields, survival, fertility, somatic cell count, liveweight and feed saved on year of birth for Holsteins. The ABVs were accessed from the ADHIS and were from the August 2015 genetic-evaluation run. The regression coefficients were multiplied by 10 to approximate the genetic improvement in each trait over a 10-year period. As the ABVs for fertility were expressed as 6-week in calf rate, to align with the model to calculate emissions, the responses were converted to calving interval by dividing by –0.65 (Haile-Mariam Mekonnen, DEDJTR, pers. comm., Melbourne, 2016). Selection between 2004 and 2014 was likely to be partly using the predecessor of the BPI, which was known as the Australian profit ranking index. The realised rate of genetic gain in BPI between 2004 and 2014 was ~AU$8/year, calculated as the regression of BPI on year of birth. Predicted future rates of genetic gain were obtained from the study of Byrne *et al.* (2016) and assumed that the economic rate of genetic gain in BPI was AU$10/year, which is similar to the realised rate of genetic gain in the previous decade.

Historical and future responses to selection in CO_2-eq emissions per cow per year were calculated by multiplying the selection responses for each trait in the breeding objective by the

effect of a single unit change of the trait on CO_2-eq emissions. The sum of this response is the total CO_2-eq response to selection, which was assessed over 10 years of selection from 2004 to 2014 (historical) and from 2016 to 2026 (future).

The historical and future impact of genetic selection on CO_2-eq emissions were evaluated as (1) an estimate the impact of realised genetic selection on CO_2-eq emissions between 2004 and 2014 and (2) estimated future changes predicted between 2016 and 2026 in CO_2-eq emissions from projected rates of genetic gain where the level of milk production was assumed to be static and cow numbers were reduced (Scenario 1) and where cow numbers were assumed static and milk production increased through selection (Scenario 2). Data for cow numbers and average milk production were obtained from ADHIS. The total size of the national dairy herd was approximately 1.88 million cows in 2004–2005 and 1.74 million in 2014–2015, which is a reduction of ~140 000 (Dairy Australia 2016).

The modelled baseline herd was used to calculate the incremental change in CO_2-eq per cow per year and emission intensity of CO_2-eq per kilogram milk solids per year from genetic selection, by comparing the emission intensity of the baseline and improved herds.

Results

Changes in per-cow GHG emissions

The effects of a unit change of a trait on GHG emissions are shown in Table 2. For example, a unit change in milk protein is estimated to be associated with a GHG emission of 1.9 kg of CO_2-eq. These can be converted into annual genetic changes by multiplying by the expected, or realised, rates of genetic gain. For example, after 10 years of selection, the ABV for protein has increased by 9.2 kg, which is equivalent to an extra 17.5 kg CO_2-eq/cow.year. If it is assumed that GHG emissions associated with each change in ABV are independent of each other; then, as a result of genetic selection, the total emissions per cow have increased by 54.9 kg CO_2-eq/cow.year after 10 years of selection. The results are

presented in this way for transparency; however, very similar results were obtained from the model when trait changes were simultaneous.

Using the same approach as described above, but applied to predicted rates of genetic gain resulting from a AU$100 increase in BPI (~10 years of genetic improvement), per-cow emissions are projected to increase by 37.2 kg CO_2-eq/cow.year (Table 2), which is a 32% reduction in emission increases per cow compared with selection objectives over the previous decade. This reduction in emissions is partly because the new overall breeding objective, BPI, includes a breeding value for feed efficiency 'feed saved' and favourable responses in CO_2-eq are predicted because of improved feed utilisation that would in turn lead to 5.8 kg CO_2-eq reduction after 10 years of selection (Table 2). For selection on BPI, we also anticipate a 2.09% improvement in survival from one lactation to the next and a reduction of –21.9 kg CO_2-eq/cow.year after 10 years of selection because of this improvement. Genetic gain in fertility (reduction in calving interval) also favourably affects net emissions.

The emission intensity, which is estimated to be ~9.7 kg CO_2-eq/kg milk solids, is estimated to have reduced by 35.7 g CO_2-eq/kg milk solids.year through selection in the previous decade and is predicted to reduce to 29.5 g CO_2-eq/kg milk solids.year through selection on BPI.

Selection over the past 10 years

Over the past 10 years, although per cow emissions have increased by ~55 kg CO_2-eq/cow.year after 10 years of selection, there has also been a reduction in total cow numbers of ~140 000. As shown in Table 3, if GHG emissions of the national dairy population totalled 8 498 701 t CO_2-eq per year in 2004, then by 2014 we project the annual emission has reduced to 7 961 306 t CO_2-eq per year (through genetic improvement), which is a reduction in GHG emissions of ~537 394 t CO_2-eq per year. There has also been a dilution effect, which is estimated using the bio-economic model to be ~54.9 g CO_2-eq per kg of milk

Table 2. Responses in carbon dioxided equivalents (CO_2-eq) per unit change of key traits under selection, actual historical rates of genetic gain over 10 years of selection and future predicted responses to selection over 10 years of selection on the balanced performance index and total responses in CO_2-eq for each trait under selection over 10 years

Parameter	Response (kg) CO_2-eq/unit change of trait[A]	Historic (2004–2014) Realised rate of genetic gain (10 years)[B]	Response kg CO_2-eq/cow	Future (2016–2026) Predicted rate of genetic gain (10 years)[C]	Response kg CO_2-eq/cow
Milk volume	0.1	314 kg	31.4	121 kg	12.1
Milk protein	1.9	9.2 kg	17.5	6.5 kg	12.4
Milk fat	5.1	7.5 kg	38.3	9.3 kg	47.2
Survival	−10.5	4.5%	−47.3	2.1%	−21.9
Somatic cell count	0.05	16.1 cells/mL	0.8	8.9 cells/mL	0.4
Liveweight	3.4	0.97 kg	3.3	0.07 kg	0.2
Feed saved	−1.29	−19 kg	24.5	4.5 kg	−5.8
Calving interval	5.9	−2.3 days	−13.6	−1.3 days	−7.4
Total response in CO_2-eq emissions (kg/cow)		54.9		37.2	
CO_2-eq emissions (g/kg milk solids)		35.7		29.5	

[A]Bell *et al*. (2013).
[B]ADHIS (2015).
[C]Byrne *et al*. (2016).

solids per year, which has led to a further reduction in CO_2-eq emissions of 316 801 t per year. This results in an estimated total reduction in CO_2-eq of 85 4196 t/year after 10 years (to 7 644 504 t/year), which constitutes a total reduction of 10.1% in estimated emissions in 2004.

Future Scenario 1 (fewer cows to produce the same amount of milk)

Taking the average yield of milk solids in Australia in 2014–2015 of 510 kg/year (ADHIS 2015), then after 10 years of selection on BPI (an increase of 100 BPI units), milk-solid yield is predicted to increase to 526 kg/year, assuming genetic gain of milk solids of 1.58 kg/year (Byrne *et al.* 2016). Therefore, by taking into consideration only the effects of genetic improvement, then to produce the same amount as today would require 52 126 fewer cows, i.e. 1 687 874 cows. If the baseline (obtained from the model) is 4575 kg/cow.year of total CO_2-eq emissions and genetic improvement results in an additional 37 kg/cow.year of CO_2-eq, then after 10 years of genetic improvement, having 52 126 fewer cows will result in 175 786 t CO_2-eq/year lower emissions.

After 10 years of selection, cow milk-solid production is projected to increase from 510 kg/year to 526 kg/year, as annual fat plus protein yields increase by 6.5 kg and 9.25 kg respectively. After 10 years of selection, there would be a dilution of 37.2 g CO_2-eq per kg of milk solids per year. Multiplying this by the number of cows required in 10 years producing 526 kg milk solids/year would lead to a reduction in CO_2-eq emissions of 261 694 t/year.

The total impact of dairy selection practices of 10 years of selection on GHG emissions is projected to be a reduction of 175 786 + 261 694 = 437 480 t CO_2-eq per year to 7 523 827 t (Table 3), which is ~5.5% of the total current annual dairy emissions of 7 961 306 t in 2014–2015, or 0.55% per year. If the rate of genetic gain for BPI increases by 50%, from AU$10/year to AU$15/year, through more widespread use of BPI as the primary method to select the next generation of animals, then per cow emissions could go up to 55 kg/cow.year CO_2-eq; however, even higher yields and a further reduction in the number of cows required could result in a 6.6% reduction in total current dairy emissions per year.

Future Scenario 2 (keeping cow numbers static)

Using the same assumptions as for Future Scenario 1, but assuming that the number of cows remains constant, then there would be a small increase in the total emissions of 37 kg/cow.year CO_2-eq, which would lead to an increase in emissions of 64 649 t (Table 3). However, at the same time there would be a reduction in emissions of 269 776 t as a result of higher milk-solid production diluting emissions, i.e. as per cow yield of milk solids increases from 510 kg/year to 526 kg/year. The net reduction is estimated to be a reduction of 205 127 t, which is 2.6% over 10 years of selection.

Discussion

Historically, breeding goals have been focussed entirely on the impact of the new breeding value on farmer profitability. However, breeding goals are now becoming more complex, so as to meet challenges set by concerns for environmental impact and societal implications (Boichard and Brochard 2012; Martin-Collado *et al.* 2015). For example, there has been increased interest in selecting animals on feed efficiency or enteric CH_4 emissions (de Haas *et al.* 2014). Although there is an economic cost to rising GHG concentrations, the main benefits to reducing emissions are societal and environmental, rather than incurred directly by dairy farmers.

We have shown that the national selection objective of Australia, the BPI, is expected to result in increasing per cow emissions (i.e. 37 kg CO2-eq/cow.year), although these are lower than the predictions based on realised rates of genetic gain over the previous decade (i.e. 55 kg CO_2-eq/cow.year). One of the main reasons for the reduction in GHG emissions through selection on BPI is that the realised rates of genetic gain for production traits were higher over the past 10 years than they are predicted to be over the next 10 years. The projected rates of genetic gain over the next 10 years are conservative and assume overall economic rates of genetic gain similar to those in the previous 10 years, i.e. ~AU$10/year improvement in BPI. If the rate of genetic gain per year in BPI increases by 50% (to AU$15/cow.year), which could happen if more farmers use it in their selection decisions, then the net reduction in per-cow emissions is predicted to increase to 55 kg CO_2-eq/cow.year, mainly because of the increase in production traits.

Table 3.   Rates of genetic gain and population sizes assumed for the scenarios explored and corresponding net emission levels

Future (1), fewer cows to produce the same amount of milk. Future (2), same number of cows through the 10 years. APR, Australian profit ranking index; BPI, balanced performance index; CO_2-eq, carbon dioxide equivalent

Parameter	Historic (2004–2014)	Future (1) (2016–2026)	Future (2) (2016–2026)
Change in BPI/APR per year	AU$8[A]	AU$10[B]	AU$10[B]
Cows in Year 0	1 880 000	1 740 000	1 740 000
Cows in Year 10	1 740 000	1 687 874	1 740 000
Total annual population fat + protein in Year 0 (kg)	862 040 000	887 400 000	887 400 000
Total annual population fat + protein in Year 10 (kg)	887 400 000	887 400 000	914 805 000
Year 0: GHG emissions (t CO_2-eq)	8 498 701	7 961 306	7 961 306
Year 10: GHG emissions (t CO_2-eq)	7 644 504	7 523 827	7 756 180

[A]Realised (ADHIS 2015).
[B]Predicted (Byrne *et al.* 2016).

As production per cow increases, the emission intensity, estimated at ~9.7 kg CO_2-eq per kg milk solids will continue to reduce at an estimated incremental rate of 29.5 g CO_2-eq/kg milk solids per year, which is also slightly lower than that during the past decade at 35.7 g CO_2-eq/kg milk solids per year. Notably, the estimated reduction in cow numbers (cow numbers were 1 880 000 in 2004–2005 and 1 740 000 in 2014–2015) and increased milk-solid production (861 040 t in 2004–2005 and 887 400 t in 2014–2015) suggests a bigger reduction of 84.4 g CO_2-eq/kg milk solids per year over the Past decade, presumably partly due to the reduction in cow numbers nationally, coupled with selection for genetically superior animals.

We have shown that improved efficiencies of production associated with selection for improved survival, feed utilisation and calving interval will reduce GHG emissions from Australian dairy herds (Table 2). Jones *et al.* (2008) calculated that the genetic improvement in economic and production efficiency of dairy cows in the UK over the past 20 years has reduced GHG emissions per unit product by 0.8% per year and these authors predicted that it will continue to reduce emissions at a rate of 0.5% per year over the next 15 years. A reduction of 0.6% per year in GHG emissions per unit product was found by Capper *et al.* (2009) in the US over a 63-year period. The historical and projected future reductions in GHG emissions from the Australian dairy sector of 1.0% and 0.3–0.6% per year respectively, are comparable to reductions reported in the above studies. Since a large proportion of total-herd GHG emissions was associated with enteric CH_4 (0.76), this meant that future reductions in dairy emissions will reduce enteric CH_4 emissions and emissions per litre of milk produced (estimated at 18.3 g CH_4/L in the current study). Jones *et al.* (2008) found in the UK that emission intensities for CH_4 and N_2O per unit product had declined by ~1.3% and 1.5% per year respectively, over the past 20 years, and were projected to decline over the next 15 years, albeit at a slightly slower rate per year. These historical rates of decline for CH_4 are similar to those reported by Bell *et al.* (2010) for enteric CH_4 emissions per unit product of 1.1% per year for cows selected on increased milk fat and protein production compared with 1.4% per year for cows selected to represent the UK average for milk fat and protein production over a similar period.

Our calculations assumed that no selection pressure would be placed on traits with the specific objective of reducing GHG emissions. However, the selection responses described in Table 2 may result in extra feed requirements, especially as milk-production traits will increase substantially. However, per-cow feed requirements for maintenance in particular are expected to reduce, for the same level of milk production, through selection on the BPI, partly as a result of including the 'feed saved' breeding value into the overall breeding objective. An even larger reduction in GHG emissions might be achieved if breeding values for CH_4 emissions were developed and incorporated into the BPI. van de Haar and St Pierre (2006) and Chagunda *et al.* (2009) found that more energy-efficient animals produce less waste in the form of CH_4 and nitrogen excretion per unit product. Although a large proportion of the variation in enteric CH_4 emissions from ruminant animals can be explained by diet composition and feed intake (Beauchemin *et al.* 2008; Bell and Eckard 2012), there is variation in enteric CH_4 emissions among animals (de Haas *et al.* 2011; Garnsworthy

et al. 2012), which provides the opportunity to select animals on the basis of their CH_4 output. Furthermore, Bell *et al.* (2016) estimated that under UK conditions, a reasonable economic value for enteric CH_4 was £1.68 per kg CH_4. Taking into consideration that existing traits included in the Australian national breeding objective do not account for the variation in enteric CH_4 emissions, it is likely that including enteric CH_4 in multi-trait selection may help increase profit per cow and further reduce GHG emissions from Australian dairy herds. An even greater incentive to select for reduced GHG emissions may arise if a carbon price were to be introduced to agriculture in Australia.

As with the inclusion of the feed saved trait in the BPI, genomic selection could be used to select animals for reduced CH_4 output (de Haas *et al.* 2011). Assuming a positive genetic correlation between feed efficiency and CH_4 emissions, with an estimated range from 0.18 to 0.84, it can be inferred that selecting cows that are more efficient will reduce CH_4 production, possibly in the order of 1.1–2.6% per year (de Haas *et al.* 2011), which is even higher than the 1% reduction in total GHG emissions estimated in the current study over the past decade. However, building a sufficiently large dataset for genetic-parameter estimation has been challenging, as phenotype data is scarce and expensive to collect.

In conclusion, there has been a reduction in overall cow numbers over the past decade, while per-cow production has increased. By considering the genetic changes (in breeding values) over this time frame, there has been a net reduction of ~1.0%/year in total emissions from the dairy industry. Future projections, based on modest annual improvements in the BPI of AU$10/year, suggest that national dairy emissions will continue to reduce, albeit at a slightly lower rate of 0.3–0.6% depending on future changes in milk production and cow numbers, with a greater predicted reduction if milk production were to be kept the same compared with if cow numbers were to be kept static. Predicted genetic improvements in survival, feed utilisation and reproductive performance will help reduce GHG emissions per cow and per unit product.

Acknowledgements

References

ADHIS (2015) Australian dairy herd improvement report 2015. Available at http://adhis.com.au/v2/sitev2.nsf/(ContentByKey)/DataServicesStatistics? open [Verified July 2016]

Beauchemin K, Kreuzer M, O'mara F, McAllister T (2008) Nutritional management for enteric methane abatement: a review. *Animal Production Science* **48**, 21–27. doi:10.1071/EA07199

Bell MJ, Eckard RJ (2012) Reducing enteric methane losses from ruminant livestock – its measurement, prediction and the influence of diet. *InTech* doi:10.5772/50394

Bell M, Wall E, Russell G, Morgan C, Simm G (2010) Effect of breeding for milk yield, diet and management on enteric methane emissions from dairy cows. *Animal Production Science* **50**, 817–826. doi:10.1071/AN10038

Bell MJ, Eckard RJ, Pryce JE (2012) Breeding dairy cows to reduce greenhouse gas emissions. *InTech.* doi:10.5772/50395

Bell M, Eckard R, Haile-Mariam M, Pryce J (2013) The effect of changing cow production and fitness traits on net income and greenhouse gas emissions from Australian dairy systems. *Journal of Dairy Science* **96**, 7918–7931. doi:10.3168/jds.2012-6289

Bell M, Pryce J, Wilson P (2016) A comparison of the economic value for enteric methane emissions with other biological traits associated with dairy cows. *American Research Journal of Agriculture* **2**, 1–17.

Boichard D, Brochard M (2012) New phenotypes for new breeding goals in dairy cattle. *Animal* **6**, 544–550. doi:10.1017/S1751731112000018

Byrne T, Santos B, Am P, Martin-Collado D, Pryce J, Axford M (2016) New breeding objectives and selection indices for the Australian dairy industry. *Journal of Dairy Science* **99**, 8146–8167. doi:10.3168/jds.2015-10747

Capper JL, Cady R, Bauman D (2009) The environmental impact of dairy production: 1944 compared with 2007. *Journal of Animal Science* **87**, 2160–2167. doi:10.2527/jas.2009-1781

Chagunda M, Römer D, Roberts D (2009) Effect of genotype and feeding regime on enteric methane, non-milk nitrogen and performance of dairy cows during the winter feeding period. *Livestock Science* **122**, 323–332. doi:10.1016/j.livsci.2008.09.020

Dairy Australia (2016) Cows and farms. Available at http://www.dairyaustralia.com.au/Markets-and-statistics/Farm-facts/Cows-and-Farms.aspx [Verified August 2016]

DCCEE (2016a) 'Australian greenhouse emissions information system.' (Department of Climate Change and Energy Efficiency: Canberra). Available at http://ageis.climatechange.gov.au/NGGI.aspx [Verified 22 July 2016]

DCCEE (2016b) Australian National Greenhouse Accounts, National Inventory report 2014. Australian Government Department of Climate Change and Energy Efficiency, Canberra. Available at http://www.environment.gov.au/climate-change/greenhouse-gas-measurement/publications/national-inventory-report-2014 [Verified 22 July 2016]

de Haas Y, Windig J, Calus M, Dijkstra J, De Haan M, Bannink A, Veerkamp R (2011) Genetic parameters for predicted methane production and potential for reducing enteric emissions through genomic selection. *Journal of Dairy Science* **94**, 6122–6134. doi:10.3168/jds.2011-4439

de Haas Y, Pryce J, Berry D, Veerkamp R (2014) Genetic and genomic solutions to improve feed efficiency and reduce environmental impact of dairy cattle. In 'Proceedings of the 10th world congress of genetics applied to livestock production'. (American Science of Animal Science: IL)

Emmans G (1994) Effective energy: a concept of energy utilization applied across species. *British Journal of Nutrition* **71**, 801–821. doi:10.1079/BJN19940188

FAO (2010) 'Greenhouse gas emissions from the dairy sector: a life cycle assessment.' (FAO: Rome)

Garnsworthy P, Craigon J, Hernandez-Medrano J, Saunders N (2012) Variation among individual dairy cows in methane measurements made on farm during milking. *Journal of Dairy Science* **95**, 3181–3189. doi:10.3168/jds.2011-4606

Hegarty R, Goopy J, Herd R, McCorkell B (2007) Cattle selected for lower residual feed intake have reduced daily methane production. *Journal of Animal Science* **85**, 1479–1486. doi:10.2527/jas.2006-236

IPCC (2007) Climate change 2007, mitigation of climate change. (The Intergovernmental Panel on Climate Change) Available at https://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4_wg3_full_report.pdf [Verified July 2016]

Jones HE, Warkup CC, Williams A, Audsley E (2008) The effect of genetic improvement on emission from livestock systems. In 'Proceedings of the European Association of Animal Production', 24–27 August, Vilnius, Lithuania. p. 28.

Martin-Collado D, Byrne T, Am P, Santos B, Axford M, Pryce J (2015) Analyzing the heterogeneity of farmers' preferences for improvements in dairy cow traits using farmer typologies. *Journal of Dairy Science* **98**, 4148–4161. doi:10.3168/jds.2014-9194

Moate PJ, Deighton MH, Williams SRO, Pryce JE, Hayes BJ, Jacobs JL, Eckard RJ, Hannah MC, Wales WJ (2016) Reducing the carbon footprint of Australian milk production by mitigation of enteric methane emissions. *Animal Production Science* **56**, 1017–1034. doi:10.1071/AN15222

Pryce J, Gonzalez-Recio O, Nieuwhof G, Wales W, Coffey M, Hayes B, Goddard M (2015) Hot topic: definition and implementation of a breeding value for feed efficiency in dairy cows. *Journal of Dairy Science* **98**, 7340–7350. doi:10.3168/jds.2015-9621

Stott A, Veerkamp R, Wassell T (1999) The economics of fertility in the dairy herd. *Animal Science* **68**, 49–58.

van de Haar MJ, St Pierre N (2006) Major advances in nutrition: relevance to the sustainability of the dairy industry. *Journal of Dairy Science* **89**, 1280–1291. doi:10.3168/jds.S0022-0302(06)72196-8

Wall E, Simm G, Moran D (2010) Developing breeding schemes to assist mitigation of greenhouse gas emissions. *Animal* **4**, 366–376. doi:10.1017/S175173110999070X