climate X change    Scotland's centre of expertise connecting climate change research and policy

# Policy Brief:
# How do different livestock types, sizes and breeds differ in their greenhouse gas emissions?

*Richard J. Dewhurst, SRUC Dairy Research and Innovation Centre, Dumfries*
*Gemma Miller, SRUC Beef and Sheep Research Centre, Edinburgh*
*March, 2019*

## Background

Farmers in Scotland produce the food that we eat, but in the process also contribute to the emission of greenhouse gases. If we want to lower the emissions from meat production, a first step is to understand what is currently known about the animals that we rear in Scotland, and how greenhouse gas emissions vary between breeds.

## Key Findings

1. Since cattle have not been bred on the basis of their emissions, any differences are based on feed intake or production system, and no clear difference was found between breeds.
2. For breeds that have high productivity, methane emissions may be lower per kilogram of beef produced because they consume a smaller amount of feed. In the same way, an animal that can digest its food more quickly will generate fewer emissions as there is less time for processing in the stomach. So, breeds selected for higher production will have reduced greenhouse gas emissions, particularly when expressed relative to production;
3. On the other hand, the evidence shows that selective breeding can be linked with problems of ill health, increased death rates and reduced fertility, and so overall reductions in greenhouse gas emissions will depend on minimising these risks – for example by having an appropriate breed for the environment or management system.
4. We found evidence of significant genetic variation in greenhouse gas emissions within all breeds. This means there is potential to reduce emissions of some gases (e.g. nitrous oxide and ammonia), but shows less promise for methane.
5. It is not clear whether selecting animals for their ability to convert feed efficiently will have a beneficial effect on methane. Whilst there are relatively few studies, the current evidence suggests that selection for feed efficiency may increase emissions from livestock based on a high-forage diet.

ClimateXChange is Scotland's Centre of Expertise on Climate Change, providing independent advice, research and analysis to support the Scottish Government as it develops and implements policies on adapting to the changing climate and the transition to a low carbon society.

www.climatexchange.org.uk

# Contents

# Evidence Base

Agriculture accounts for the second-largest greenhouse gas (GHG) emissions in Scotland, and the Scottish Government is exploring different ways that this can be tackled. It is important to understand differences that can be detected between different breeds of livestock, as options are developed, and this report reviews the evidence. The focus of this report is on work with cattle, though some relevant work with sheep is also included.

The evidence for the effects of breeds on greenhouse gas emissions intensity and its components is presented against six different criteria:

1. *Breed differences*
2. *Effects of production level*
3. *Health and fertility effects*
4. *Variations within breeds*
5. *Matching breeds to environments*
6. *Effects related to feed conversion efficiency*

## Point 1: Breed Differences

Since cattle have not been selected directly for methane emissions or Nitrogen-use efficiency (NUE), there is no reason to expect much difference between breeds in these traits - apart from small effects related to selection for production level (see point 2). The following sections set out evidence from direct comparisons of cattle (and sheep) breeds and crosses:

**Methane emissions**

Nine recent studies comparing methane yield of different breeds/crosses were identified (3 with beef cattle, 1 with dairy cows, 1 with dairy and dairy beef crosses, and 4 with sheep). These studies showed that differences in methane emissions are attributed to the production system, diet type and dry matter feed intake (DMI) of the animal and no breed effects were identified. The relevant conclusions are quoted directly from the papers:

1. *De Mulder et al. 2018: <u>Holstein-Friesian (HF) vs. Belgian Blue (BB) heifers</u>: "After correcting for DMI, the methane yield was not significantly different between HF and BB heifers, though numerically HF heifers had an 8% lower methane yield ($CH_4$ per DMI) as compared to BB heifers……. Our results suggest that breed related factors influence the bacterial community composition, while the variation in methane emission levels can be attributed mainly to the feed intake of the animals."*
2. *Duthie et al. 2017 (study conducted in Scotland): <u>Charolais crosses vs. Luing steers</u>: "The experiment was of a 2×2 factorial design, comprising two breeds (crossbred Charolais (CHX); purebred Luing (LU)) and two diets (concentrate-straw or silage-based). …. Breed of steer did not influence methane production."*
3. *Fraser et al. 2015: <u>Welsh Mountain vs. Texel cross lambs</u>: "Although total daily $CH_4$ emissions were lower for the WM lambs than for the TexX lambs (13·3 v. 15·7 g/day, respectively) when offered fresh forage, the yield of $CH_4$ per unit DMI was similar for the two breed types (16·4 v. 17·7 g $CH_4$/kg DMI)."*
4. *Fraser et al. 2014: <u>Limousin cross vs. Welsh Black steers</u>: "While emissions per unit feed intake were similar for the lowland and upland systems, $CH_4$ emissions per unit of live-weight gain (LWG) were substantially higher when the steers grazed the poorer quality hill pasture (760 vs 214 g $kg^{-1}$ LWG; s.e.d. = 133.5 g $kg^{-1}$ LWG; $P<0.001$). Overall any effects of breed type were relatively small relative to the combined influence of pasture type and location."*

5. *Zhao et al (2017): <u>Scottish Blackface vs. Swaledale x Scottish Blackface ewes</u>: "Genotypes of sheep had no effect on any variable in feed intake, digestibility, $CH_4$ emissions or N utilization."*
6. *Flay et al (2019): <u>Holstein-Friesian vs. Jersey heifers</u>: "Jersey heifers produced less $CH_4$/d, but not $CH_4$/kg of DMI or $CH_4$/kg of BWg"*
7. *Zhao et al (2016): <u>Scottish Blackface vs. Swaledale x Scottish blackface hoggetts</u>: "There was no significant difference in $CH_4$ emission rate or N utilisation efficiency when compared between Scottish Blackface and Swaledale × Scottish Blackface."*
8. *Zhao et al (2015): <u>Texel vs. Highlander lambs</u>: "Texels produced more $CH_4$/DMI (g/kg) than Highlanders ($P = 0.044$)…… Neither breed nor sex had an effect on N utilization efficiency ($P > 0.05$)." [though note that this was only 21.9 versus 21.0 g methane per kg DMI]*
9. *Richmond et al (2015): <u>Holstein-Friesian vs. Charolais cross steers and heifers</u>: "Mean daily $CH_4$ emissions, expressed as g/kg DMI, were not significantly different between the UG and LG sites. Furthermore, there were no significant differences between experimental periods, genders or breeds and no significant interactions for these parameters."*

In their large meta-analysis of 89 studies with dairy and beef cattle conducted around the world between 1992 and 2015 (217 treatment means), Liu et al. (2017) identified significant differences in methane emissions between breeds as follows (values expressed as a % of Gross Energy intake): Thai native (5 studies; 8.4%); Brown Swiss (10 studies; 7.0%); Brahman (9 studies; 6.8%); Charolais (6 studies; 6.6%); Hereford (1 study; 6.3%); Angus (13 studies; 6.0%); Simmental (2 studies; 5.8%); Jersey (4 studies; 5.6%); Holstein (52 studies; 5.3%); Swedish Red (5 studies; 4.7%); Yak (3 studies; 4.8%); and Nellore (6 studies; 3.3%). However, most of the variation was related to differences in the diets and management of cattle rather than breed per se. Feeding practices are well-known to affect methane emissions intensity and rates of Nitrogen excretion – effects which have been the subject of previous comprehensive reviews (e.g. Knapp et al. (2014) for methane emissions intensity and Spek et al. (2013) for Nitrogen excretion). It is also apparent that the mean values for common breeds in Scotland were all close to 6% of Gross Energy intake.

**Nitrogen-use efficiency (NUE)**

Few studies were identified comparing NUE between breeds. Two studies found no difference between Jersey, Holstein-Friesian and Holstein-Friesian x Jersey cows (Rius *et al*, 2010; Kristensen *et al*, 2015). A further two studies found no difference in NUE between sheep breeds (Zhao *et al*, 2015, 2016). No studies relevant to Scotland (or the UK) were identified for beef cattle. A review of energy and N use efficiency in dairy cows (Phuong *et al*, 2013) highlighted the lack of studies which consider breed as a factor.

Overall there is little evidence for differences in emissions intensity between breeds, when compared at a similar level of production (see point 2). The absence of direct selection means that there may still be considerable between-animal variation within breeds (see point 4).

## Point 2: Effects of production level

There are two mechanisms related to production level that can lead to a reduction in greenhouse gas emissions, expressed per kg DMIor per kg of product (milk or meat):

*(1) The 'dilution of maintenance' effect – at higher levels of production a smaller proportion of feed intake (and hence methane emissions) relates to animal maintenance costs.*

*(2) Higher rates of passage of feed through the rumen of higher producing animals means that there is less potential for fermentation (and hence less production of methane).*

The effect of production level is more pronounced when methane emissions are expressed relative to production (i.e. per L milk or kg of beef) because of the 'dilution of maintenance' effect whereby a greater proportion of energy intake is directed towards productive as opposed to maintenance functions.

Analysis of results from the Langhill Breeding Experiment by Ross et al. (2014) showed that both genetic and management approaches to increasing milk production can lead to a reduction in greenhouse gas emissions intensity. Improving genetic merit led to a 9% reduction, whilst implementing a low forage (high concentrate) diet led to a 16% reduction in emissions intensity.

A number of studies have brought together results from many experiments in order to identify the underlying relationship between methane emissions and production (or feed intake level). These analyses confirmed the anticipated reduction in methane (g/kg DM intake) with increasing production (feed intake) level:

1. *The Meta-analysis of Dewhurst et al. (2019) from studies with grazing cattle identified the following relationship:*

   Methane (g/kg DMI) = 31.7 (s.e. = 1.25)$^{***}$ – 1.13 (s.e. = 0.126) DMI (kg/day)$^{***}$ ($R^2$ = 55.2; residual s.d. = 3.37; $P < 0.001$; n = 65)

2. *The much larger meta-analysis conducted by Liu et al. (2017) brought together results from 89 peer-reviewed studies with dairy or beef cattle reported between 1992 and 2015 (217 treatment means from grazing or housed cattle) and concluded: "Higher energy digestibility of feed and higher energy intake level of cattle resulted in a lower percentage of digestible energy intake being converted to $CH_4$"*

The observed reduction in methane emissions with increasing production level with cattle was confirmed in sheep by Zhao et al (2016, 2017).

A similar effect of production level also applies to NUE, though again effects will be small within the range of breeds used in Scotland and the UK. In an Irish study, Prendiville et al (2009) showed that Holstein Friesian cows produced less milk solids per Kg DMI compared to Jersey and Jersey cross HF cows and this would have a small effect on NUE.

## Point 3: Health and fertility effects

Inefficiencies related to infertility, ill health and mortality will all lead to increased GHG emissions intensity since emissions are spread across less output of milk or meat. Rauw et al (1998) reviewed the potential undesirable side-effects of genetic selection for increased productivity of dairy cattle. As a result of some early negative experiences, most breeders and Breed Societies are well aware of these potential issues and so promote multi-trait approaches to breeding and selection indices that incorporate many traits. Nonetheless, there remains the potential for correlated genetic effects to build up slowly over time and breeders need to be vigilant.

The history of the Holstein-Friesian breed illustrates that reductions in emissions intensity (g/L milk) will only be achieved if the benefits of increased production levels are not offset by increased health problems, mortality, infertility etc. Examples of issues which may reduce the positive effects of selection for increased productivity (milk yield or growth rate) on GHG emissions intensity include:

The decreased fertility and consequent increased involuntary culling rate of Holstein-Friesian cattle as a consequence of single trait selection for milk production during the later decades of the last century (Royal et al. 2000).

Feto-maternal disproportion (calves too large for natural birth) is a problem associated with double muscled breeds such as Belgian and British Blue (Kolkman *et al*, 2010). Belgian Blues have a high rate of dystocia (difficult calvings), particularly for bull calves (Bleul, 2011). Difficult calvings can lead to death or premature culling of the cow and high mortality or poor performance of the calf.

## Point 4: Variation within breeds

Whilst the above evidence confirms that there are only small differences between livestock breeds in GHG emissions, there is a growing body of evidence of genetic variation GHG emissions (methane or N) within breeds:

- *Pickering et al (2015) – provided an early review of progress in evaluating genetic effects on livestock greenhouse gas emissions.*
- *Jonker et al (2018) – presented heritabilities for methane emissions from sheep in a New Zealand breeding programme;*
- *Kittelmann et al (2014) – showed differences in bacterial communities in the rumen of high- and low-methane emitting sheep, suggesting that there is animal genetic control over the rumen and its microbial community;*
- *Pszczola et al (2018) – showed that genes involved in controlling development of the ruminant digestive tract are related to genetic differences in methane emissions of dairy cows;*
- *Difford et al (2018) – demonstrated separate effects of the rumen metagenome and cow genome on methane emissions;*
- *Roehe et al (2016) – demonstrated differences in methane emissions from sire progeny groups (beef steers);*

Although the above studies show considerable promise in selecting for genetic variation in methane emissions, they have often shown negative effects on other aspects of productivity that may mean that there is no overall effect on methane emissions intensity. For example:

- *Pinares-Patino et al (2003) concluded: "These results suggest that sheep with lower rumen particulate FOR (i.e. longer rumen retention times) had larger rumen fills and higher fibre digestibilities and $CH_4$ yields."*
- *Goopy et al. (2014): showed reduced rumen volume and reduced rumen retention time (so potentially reduced diet digestibility) in low emitting sheep selected from a large-scale genetic study with Australian breeds.*
- *Lambe et al. (2019) showed a negative relationship between rumen volume of Scottish Blackface ewes and methane emissions – confirming the danger of losing capacity to ferment fibrous feeds (forages) by selecting for low emitting sheep.*
- *Bond et al (2019): "Daily $CH_4$ emission (g/day) increased significantly ($P < 0.001$) with an increasing dry-matter intake (DMI) and reticulo-rumen volume ($P < 0.001$). Lower methane yield (g CH4/kg DMI) was associated with shorter mean retention times of liquid ($r = 0.59$; $P < 0.05$) and particle ($r = 0.63$; $P < 0.05$) phases of the digesta in the rumen."*

## Point 5: Matching breeds to environments

Breeds have been developed to perform best under specific management and/or environmental conditions and matching breeds to systems will have important effects on emissions intensity though effects on things like health, mortality, fertility, litter sizes and production rates.

The analysis of results from the Langhill Breeding Study by Ross et al (2014) showed that the effects of genetic line (9%) and feeding strategy (16%) on methane emissions intensity can come together to deliver an overall 24% reduction in offering the best diet to the highly selected cows.

Earlier maturing beef breeds (e.g. Aberdeen Angus) are often considered to be better adapted to upland systems than later maturing breeds (e.g. Charolais) (Rook *et al*, 2014). However, there are no Scotland (or UK) relevant examples in the literature of matching breeds to environments. The majority of the literature in this area focuses on British/European beef breeds in tropical environments, where they are found to perform less well and be less fertile than in temperate climates. They are also more susceptible to environmental stressors (e.g. ticks, worms and heat) than breeds that are selected for tropical environments (Burrow, 2012).

There is some older evidence (> 10 years) supporting the statement that management system is important to maximise production efficiency. Suckler beef (Lewis *et al*, 1990), beef animals of dairy origin (Keane and Allen, 1998; McGee *et al*, 2005) and dairy bulls (Therkildsen *et al*, 1998, McGee *et al*, 2005) were found to be more efficient (and so produce less methane per kg of product) under intensive management systems than extensive systems.

Beef and dairy cattle were 6-7 months older at slaughter in extensive compared to intensive systems (Lewis *et al*, 1990; Keane and Allen, 1998; McGee *et al*, 2005). Furthermore, carcass outputs were greater from intensively managed cattle compared to extensively managed cattle (Keane and Allen, 1998; McGee *et al*, 2005).

Examples of studies looking to match breeds and systems are given below – from which it is clear that breeds and systems resulting in higher growth rates will result in reduced methane emissions intensity, but this may not always maximise profitability and product quality:

Lewis et al (1990): Charolais crosses in US - "Cattle from the Ext system were heavier ($P < 0.01$) before (388 vs 233 kg) and after (595 vs 531 kg) the finishing phase than Intensive system cattle. During finishing, cattle from the Extensive system made more rapid gains (1.70 vs 1.36 kg/d) and consumed more feed (12.4 vs 8.5 kg/d, 2.52 vs 2.194 of average BW) but were less efficient (0.137 vs 0.160, gain/feed) than cattle from the Intensive system ($P <0.05$). Extensive systems of beef production produced more total kilograms of beef per animal but they were 196 d older at slaughter".

Keane and Allen (1998): Charolais x Friesian in Ireland - "The three production systems were (i) young bulls finished on silage plus concentrates and slaughtered at about 19 months of age (Intensive), (ii) steers finished on silage plus concentrates and slaughtered at about 24 months of age (Conventional), and (iii) steers finished off pasture and slaughtered at about 29 months of age (Extensive). The two slaughter weights were 640 kg (Light) and 720 kg (Heavy). All measures of carcass and muscle fatness were higher ($P < 0.05$) for the Conventional system than for the other two systems which were similar in composition. Carcass output per ha was two-fold and three-fold higher for the Conventional and Intensive systems respectively, than for the Extensive system, but gross margin per animal and per ha was highest for the Extensive system".

Therkildsen et al (1998) Friesian bulls (Germany) - "Extensively managed (wintered indoors on forage and finished at pasture) bulls slaughtered directly from pasture had a lower dressing percentage ($p < 0.05$), a higher lean content ($p < 0.05$), a much lower fat content ($p < 0.05$) and darker meat colour ($p < 0.05$) than intensively managed (housed in tie- stalls, offered concentrates *ad libitum*) bulls. Finishing- fed extensive bulls (same as extensive + additional 10 weeks on concentrates after pasture) showed no sign of compensatory gain after the grazing period. The finishing period improved the carcass quality of Extensive bulls, but the Extensive bulls were leaner ($p < 0.05$) and had a darker meat colour ($p < 0.05$) than the Intensive bulls of similar live weight (460 kg). It is concluded that a finishing period of minimum 10 weeks following the grazing period is necessary to obtain a satisfactory carcass quality of the extensively produced young bulls."

McGee et al (2005): high genetic merit Holstein, Friesian and Charolais x Holstein-Friesian bulls (Ireland) - "Compared with the intensive system (free-housed on slats – 19 month bull beef), animals on the extensive system (castrated, wintered in tie stalls, summer grazed – 25 month slaughter) had a lower ($P < 0.001$) daily live-weight gain, kill-out proportion and a lower muscle proportion in the pistol"

### Point 6: Effects related to feed conversion efficiency

There is a lot of current activity concerned with defining and selecting livestock for feed conversion efficiency (FCE). It has been suggested that increased FCE means that animals consume less feed per L of milk produced or per kg of meat produced, which implies that there would be a beneficial effect on

GHG emissions intensity since there is a very close association between DMI and GHG emissions. Residual feed intake (RFI) is an alternative feed efficiency trait (the difference between actual feed intake and intake predicted from the observed growth rate). RFI is moderately heritable (0.26 to 0.43) in both beef and dairy cattle (Basarab, *et al*, 2013), and selection for this trait would inherently reduce methane emissions per Kg of product. There is also limited evidence in the literature of breed differences in RFI. For instance, Luing steers have been shown to be more efficient than Charolais steers over a finishing period on two contrasting diets (high concentrate or forage based, Duthie *et al*, 2016). Also, early maturing breeds have been shown to have higher RFI (be less efficient) than late maturing breeds (Crowley *et al*, 2010; Berry and Crowley, 2012). This aspect needs further work to clarify effects.

Despite the above logic for a positive effect of selecting for FCE (or RFI) on GHG emissions intensity the first studies to look for such an effect have been equivocal:

**Reduction in methane emissions**

Paganoni et al (2017) working with sheep concluded: "Selecting to decrease feed intake or residual feed intake will decrease methane (genetic correlation range 0.76 to 0.90)……Given these results, the hypothesis that making sheep more feed efficient will decrease their methane production can be accepted."

There were positive relationships between RFI and $CH_4$ production in the studies with beef cattle conducted by Nkrumah et al. (2006), Hegarty et al. (2007) and Fitzsimons et al. (2013). Methane emissions intensity was 15% lower in low RFI (high feed efficiency) compared to high RFI groups.

**Increase in methane emissions**

Methane emissions intensity was 10% higher in low RFI Limousin x Friesian steers compared to high RFI groups in the study of McDonnell *et al.* (2016).

Flay et al (2019) concluded: "low RFI heifers (i.e. high feed conversion efficiency heifers) had a greater $CH_4$ yield (g/kg of DMI) on a high forage diet."

These latter authors suggested that the above discrepancy may be a consequence of the different basal diets offered in different studies. There was a negative effect of selecting for FCE on methane emissions with a high concentrate diet (Nkrumah et al (2006) and Hegarty et al (2007), whilst their own study involved a high fibre diet (dried Lucerne cubes) where the ability of rumen microorganisms to ferment fibre would be more important for feed utilisation.

This is a particular issue for Scottish production systems involving high levels of grass and forage feeding where it would be problematic if selection for FCE led to increased fibre fermentation and so increased methane emisisons. Modelling work conducted in Scotland (Wall et al., 2010) has suggested reductions in GHG emissions intensity with selection for FCE, but has not yet taken into account the potential effects of increased fibre fermentability and methane production noted above. Scottish studies in which FCE and methane emission were measured in parallel (e.g. Rooke et al.,2014; Troy et al., 2015; Duthie et al., 2016, 2017) were directed at effects of dietary treatments rather than genetic effects – new studies would be required to explore this further in a Scottish context.

# Conclusions

There is no evidence for significant differences between breeds in digestion and metabolism associated with the production of methane, utilisation of absorbed protein and excretion of urinary Nitrogen when operating at the same level of production. Differences between breeds in GHG emissions intensity may result from differences in production level (as a result of more energy being directed to productive (as opposed to maintenance) functions and increased rates of passage from the rumen). Other differences may be related to the suitability of a breed to a particular environment or management system (with effects mediated by, for example, differences in feed efficiency, fertility or mortality).

For many of the traits contributing to overall GHG emissions intensity, it is more important to consider variability within breeds, as well as between breeds. There is much current interest in selecting cattle based on FCE, but anticipated reductions in GHG emissions intensity may not materialise if increased FCE results from increased fermentability of forage fibre in the rumen. Similarly, great care is needed in breeding for reduced methane emissions as this has been associated with reduced rumen capacity or function – important traits for traditional Scottish systems based on grass and forages.

# References

Basarab, J.A., Beauchemin, K.A., Baron, V.S., Ominski, K.H., Guan, L.L., Miller, S.P. and Crowley, J.J. (2013) Reducing GHG emissions through genetic improvement for feed efficiency: effects on economically important traits and enteric methane production. *Animal* 7:303-315

Berry, D.P. and Crowley, J.J. (2012) Residual intake and body weight gain: A new measure of efficiency in growing cattle. *Journal of Animal Science* 90:109-115

Bleul, U. (2011) Risk factors and rates of perinatal and postnatal mortality in cattle in Switzerland). *Livestock Science* 135: 257-264.

Bond et al (2017). Aspects of digestive function in sheep related to phenotypic variation in methane emissions. *Animal Production Science* 59: 55-65.

Burrow, H.M. (2012) Importance of adaptation and genotype X environment interactions in tropical beef breeding systems. *Animal* 6:729-740

Crowley, J.J., McGee, M., Kenny, D.A., Crews Jr., D.H., Evans, R.D. and Berry, D.P. (2010) Phenotypic and genetic parameters for different measures of feed efficiency in different breeds of Irish performance-tested beef bulls. *Journal of Animal Science* 88:885-894

De Mulder, T., Peiren, N., Vandaele, L., Ruttink, T., De Campeneere, S., Van de Wiele, T and Goosens, K. (2018). Impact of breed on the rumen microbial community composition and methane emissions of Holstein Friesian and Belgian Blue heifers. *Livestock Science* 207: 38-44.

Dewhurst, R.J. et al (2019). Diet effects on methane emissions from grazing cattle measured using the sulphur hexafluoride (SF6) technique. Advances in Animal Biosciences (BSAS Annual Meeting).

Difford, GF et al (2018). Host genetics and the rumen microbiome jointly associate with methane emisisons in dairy cows. *PLOS Genetics* 14: e1007580.

Duthie, C-A., Rooke, J.A., Troy, S., Hyslop, J.J., Ross, D.W., Waterhouse, A., and Roehe, R. (2016) Impact of adding nitrate or increasing the lipid content of two contrasting diets on blood methaemoglobin and performance of two breeds of finishing steers. *Animal* 10:786-795

Duthie, C-A., Haskell, M., Hyslop, J.J., Waterhouse, A., Wallace, R.J., Roehe, R. and Rooke, J.A. (2017). The impact of divergent breed types and diets on methane emissions, rumen characteristics and performance of finishing beef cattle*. Animal* 11: 1762-1771.

Fitzsimons, C., Kenny, D.A., Deighton, M.H., Fahey, A.G. and McGee, M. (2013) Methane emissions, body composition, and rumen fermentation traits of beef heifers differing in residual feed intake. *Journal of Animal Science* 91: 5789-5800

Flay, H.E., Kun-Sherlock, B., Macdonald, K.A., Camara, M., Lopez-Villalobos, N., Donaghy, D.J. and Roche, J.R. (2019). Hot Topic: Selecting cattle for low residual feed intake did not affect daily methane production but increased methane yield. *Journal of Dairy Science* 102: 2708-2713.

Fraser, M.D., Fleming, H.R. and Moorby, J.M. (2014). Traditional vs modern: role of breed type in determining enteric methane emissions from cattle grazing as part of contrasting grassland-based systems. *PLOS One* 9:e107861.

Fraser, M.D., Fleming, H.R., Theobald, V.J. and Moorby, J.M. (2015). Effect of breed and pasture type on methane emissions from weaned lambs offered fresh forage. *Journal of Agricultural Science*

Goopy, J.P., Donaldson, A., Hegarty, R., Vercoe, P.E., Haynes, F., Barnett, M. and Oddy, V.H. (2014). Low-methane yield sheep have smaller rumens and shorter rumen retention time. *British Journal of Nutrition* 111: 577-585.

Hegarty, R. S., Goopy, J.P., Herd, R.M. and McCorkell, B. (2007). Cattle selected for lower residual feed intake have reduced daily methane production. *Journal of Animal Science* 85: 1479–1486.

Johnson, K. A., and Johnson, D. E. (1995).Methane emissions from cattle. *Journal of Animal Science* 73: 2483–2492.

Jones, F.M., Phillips, F.A., Naylor, T. and Mercer, N.B. (2011) Methane emissions from grazing Angus beef cows selected for divergent residual feed intake. *Animal Feed Science and Technology* 166-167:302-307

Jonker et al 2018 Genetic parameters of methane emissions determined using portable accumulation chambers in lambs and ewes grazing pasture and genetic correlations with emissions determined in respiration chambers. *Journal of Animal Science* 96: 3031-3042.

Kolkman, I., Opsomer, G., Aerts, S., Hoflack, G., Laevens, H. and Lips, D. (2010) Analysis pf body measurements of newborn purebred Belgian Blue calves. *Animal* 4: 661-671.

Keane, M.G. and Allen, P. (1998) Effects of production system and intensity on performance, carcass composition and meat quality of beef cattle. *Livestock Production Science* 56:203-214

Kittelmann, S., Pinares-Patino, C.S., Seedorf, H., Kirk, M.R., Ganesh, S., McEwan, J.C. and Janssen, P.H. (2014) Two different bacterial community types are linked with the low-methane emission trait in sheep. *PLOS One* 9: e103171.

Knapp, J.R., Laur, G.L., Vada, P.A., Weiss, W.P. and Tricarico, J.M. (2014). Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *Journal of Dairy Science* 97: 3231-3261.

Kristensen, T., Jensen, C., Ostergaard, S., Weisbjerg, M.R., Aaes, O., Nielsen, N.I. (2015) Feeding, production, and efficiency of Holstein-Friesian, Jersey, and mixed-breed lactating dairy cows in commercial Danish herds. *Journal of Dairy Science* 98: 263-274.

Lambe, N.R. et al (2019). Prediction of methane emissions in sheep using computed tomography (CT) measurements of rumen volume. Advances in Animal Biosciences (BSAS Annual Meeting).

Lewis, J.M., Klopfenstein, T.J., Stock, R.A. and Nielsen, M.K. (1990) Evaluation of intensive vs extensive systems of beef production and the effect of level of beef cow milk production on postweaning performance. *Journal of Animal Science* 68: 2517-2524

Liu, Z., Liu, Y., Shi, X., Wang, J., Murphy, J.P., and Maghirang, R. (2017). Enteric methane conversion factor for *dairy and beef cattle: effects on feed digestibility and intake level.* Transactions of the ASABE 60: 459-464.

McDonnell, R.P., Hart, K.J., Boland, T.M., Kelly, A.K., McGee, M. and Kenny, D.A. (2016) Effect of divergence in phenotypic residual feed intake on methane emissions, ruminal fermentation, and apparent whole-tract digestibility of beef heifers across three contrasting diets. *Journal of Animal Science* 94:1179-1193

McGee, M., Keane, M.G., Neilan, R., Moloney, A.P. and Caffrey, P.J. (2005) Production and carcass traits of high genetic meric Holstein, standard dairy genetic merit Friesian and Charolais x Holstein-Friesian male cattle. *Irish Journal of Agricultural and Food Research* 44:215-231

Nkrumah, J. D., Okine, E.K., Mathison, G.W., Schmid, K., Li, C., Basarab, J.A., Price, M.A., Wang, Z. and Moore, S.S. (2006). Relationships of feedlot feed efficiency, performance, and feeding behaviour with metabolic rate, methane production, and energy partitioning in beef cattle. *Journal of Animal Science* 84: 145–153.

Paganoni, B., Rose, G., Macleay, C., Jones, C., Brown, D.J., Kearney, G., Ferguson, M. and Thompson, A.N. (2017) More feed efficient sheep produce less methane and carbon dioxide when eating high-quality pellets. *Journal of Animal Science* 95:3839-3850

Phuong, H.N., Friggens, N.C., de Boer, J.M. and Schmidely, P. (2013) Factors affecting energy and nitrogen efficiency of dairy cows: A meta-analysis. *Journal of Dairy Science* 96: 7245-7259.

Pinares-Patino et al 2003. Rumen function and digestion parameters associated with differences between sheep in methane emissions when fed chaffed Lucerne hay. *Journal of Agricultural Science* 140: 205-214.

Prendiville, R., Pierce, K.M. and Buckley, F. (2009) An evaluation of production efficiencies among lactating Holstein-Friesian, Jersey, and Jersey x Holstein-Friesian cows at pasture. *Journal of Dairy Science* 92:6179-6185

Pszczola et al 2018 Genome-wide association identifies methane production level relation to genetic control of digestive tract development in dairy cows. *Scientific Reports* 8:15164.

Rauw, W.M., Kanis, E., Noordhuizen-Stassen, E.N. and Grommers, F.J. (1998) Undesirable side effects of selection for high production efficiency in farm animals: a review. *Livestock Production Science* 56:15-33

Richmond, A.S., Wylie, A.R.G., Laidlaw, A.S. and Lively, F.O. (2015) Methane emissions from beef cattle grazing on semi-natural upland and improved lowland grasslands. *Animal* 9:130-137

Rius, A.G., McGuilliard, M.L., Umberger, C.A. and Hanigan, M.D. (2010) Interactions of energy and predicted metabolizable protein in determining nitrogen efficiency in the lactating dairy cow. *Journal of Dairy Science* 93: 2034-2043.

Roehe, R., Dewhurst, R.J., Duthie, C.-A., Rooke, J.A., McKain, N., Ross, D.W. Hyslop, J.J., Waterhouse, A., Freeman, T.C., Watson, M. and Wallace, R.J. (2016). Bovine host genetic variation influences rumen microbial methane production with best selection criterion for low methane emitting and efficiently feed converting hosts based on metagenomic gene abundance. *PLoS Genetics* 12: e1005846.

Rook, A.J., Dumont, B., Isselstein, J., Osoro, K., Wallis De Vries, M.F., Parente, G. and Mills J. (2004). Matching type of livestock to desired biodiversity outcomes in pastures – a review. *Biological Conservation* 119: 137–150.

Rooke, J. A.; Wallace, R. J.; Duthie, C.-A.; et al. (2014). Hydrogen and methane emissions from beef cattle and their rumen microbial community vary with diet, time after feeding and genotype. *British Journal of Nutrition* 112: 398-407.

Ross, S. A., Chagunda, M.G.G., Topp, C.F.E. (2014) Effect of cattle genotype and feeding regime on greenhouse gas emissions intensity in high producing dairy cows. *Livestock Science* 170:158-171

Royal, M.D., Darwash, A.O., Flint, A.P.F., Webb, R., Woolliams, J.A. and Lamming, G.E. (2000). Declining fertility in dairy cattle: changes in endocrine and traditional measures of fertility. *Animal Science* 70: 487-501.

Spek, J.W., Dijkstra, J., van Duinkerken, G., Hendriks, W.H. and Bannink, A. (2013). Prediction of urinary nitrogen and urinary urea nitrogen excretion by lactating dairy cattle in northwest Europe and North America: A meta-analysis. *Journal of Dairy Science* 96: 4310-4322.

Therkildsen, M., Vestergaard, M., Jensen, L.R. Andersen, H.R. and Sejrsen, K. (1998) Effect of feeding level, grazing and finishing on growth and carcass quality of young Friesian bulls, *Acta Agriculturae Scandinavica, Section A — Animal Science* 48: 193-201

Troy, S. M.; Duthie, C-A.; Hyslop, J. J.; et al. (2015). Effectiveness of nitrate addition and increased oil content as methane mitigation strategies for beef cattle fed two contrasting basal diets. *Journal of Animal Science* 93: 1815-1823.

Wall, E., Simm, G. and Moran, D. (2010). Developing breeding schemes to assist mitigation of greenhouse gas emissions. *Animal* 4: 366-376.

Zhao, Y.G., Aubry, A., O'Connell, N.E., Annett, R. and Yan, T. (2015). Effects of breed, sex and concentrate supplementation on digestibility, enteric methane emissions, and nitrogen utilization efficiency in growing lambs offered fresh grass. *Journal of Animal Science* 93: 5764-5773.

Zhao, Y.G., Aubry, A., Annett, R., O'Connell, N.E. and Yan, T. (2016). Enteric methane emissions and nitrogen utilisation efficiency for two genotype of hill hoggets offered fresh, ensiled and pelleted ryegrass. *Livestock Science* 188: 1-8.

Zhao, Y.G., O'Connell, N.E. and Yan, T. (2016). Prediction of enteric methane emissions from sheep offered fresh perennial ryegrass (*Lolium perenne*) using data measured in indirect open-circuit respiration chambers. *Journal of Animal Science* 94: 2425-2435.

Zhao, Y.G., Annett, R. and Yan, T. (2017). Effects of forage types on digestibility, methane emissions and nitrogen utilization efficiency in two genotypes of hill ewe. *Journal of Animal Science* 95: 3762-3771.