Proceedings, 10th World Congress of Genetics Applied to Livestock Production

# Genetic improvement options for the cost effective reduction of greenhouse gas emissions from ruminant production systems

**E. Wall[1,2], V. Eory[1,2], M. MacLeod[1] and D Moran[1,2]**
[1]SRUC, Edinburgh, EH9 3JG, United Kingdom. [2]ClimateXChange, Edinburgh EH8 9AA, United Kingdom.

**ABSTRACT:** This paper describes a framework to estimate the greenhouse gas (GHG) abatement potential of range of animal and system management options, including genetic improvement and estimates their relative cost effectiveness. The potential cost effective abatement that could be achieved in UK livestock by 2022 was estimated to range from 1.266 - 5.02$MtCO_2e$, with a central feasible potential of 2.68 $MtCO_2e$ represents around 5% of the 2006 UK agricultural GHG emissions. All genetic improvement options studied, including the establishment of direct recording of feed efficiency, proved to be cost effective option for reducing GHG emissions in the short, medium and longer term. Moreover, genetic improvement has little additional costs once systems have been established and impacts are cumulative and therefore is a highly sustainable option for ongoing reductions.

**Keywords:** Greenhouse gases; Production efficiency; Methane; Dairy/Beef Cattle

## Introduction

It has been estimated that agriculture accounted for 10–12% of global anthropogenic greenhouse gas (GHG) emissions in 2005 (Smith et al., 2008). Livestock systems are a source of greenhouse gas (GHG) emissions, particularly methane ($CH_4$) and nitrous oxide ($N_2O$). Livestock account for up to 40% of the world $CH_4$ production, of with 80% comes from enteric fermentation and 20% from anaerobic digestion in manure (Steinfeld et al., 2006). Agriculture accounts for 64% of global $N_2O$ emissions mainly from the use of organic and inorganic fertilizers. Mitigating, or abating, GHG from livestock can play a vital role in providing solutions to the UK's and EU's overall climate change obligations.

The main abatement options from the livestock sector, independent of grazing/pasture management, are through the efficiencies with which ruminant animals utilize their diet and manure management. Options include breed selection, selecting larger but faster growing breeds (Jones et al., 2008), or through manipulation of dietary regimes (e.g., Moss et al., 2000). The latter option could include adoption of zero grazing and higher concentrate feed usage, resulting in a greater reliance on housed systems. Dietary supplements could be used to improve the digestibility of feed. More careful management of waste products, for example through improved slurry storage (e.g., covered) facilities, also offers potential emission reductions. Although there are a range of management options to reduce emissions from livestock systems, it is less clear which of these options (and range of options) can deliver the most economically efficient reductions in emissions.

Attempts to abate GHG emissions should first target those options that are cost efficient. As there is unlikely to be one "silver bullet" option to abate GHG from livestock system we can use environmental economic approaches to categorize the costs and efficacies of alternative approaches and come up with an optimized suite of mitigation options that work in harmony rather than in conflict. Further, you can identify the options that are sustainable in the short, medium and longer term. The methodology used in this study examined abatement schedules or marginal abatement cost curves (MACC), which show the relative cost of greenhouse gas mitigation by alternative mitigation methods and technologies. MACC analysis offers a representation of costs and abatement potential that is built up from a bottom-up analysis of data on mitigation options within respective economic sectors, which in the case of this study is focusing on agriculture. These mitigations are projected to be adopted over and above a baseline of what would normally happen, thereby giving rise to extra abatement potential. This information provides a basis for deriving a sector greenhouse gas budget that is based on a cost-effectiveness analysis. These curves can then be used to determine a notional budget based on a reference cost of abatement that might be the shadow price of carbon (SPC), an emissions trading price, or any other financial or economic threshold. The resulting budget can then be used by government to negotiate with emitting sectors and to develop a policy route map for affecting emissions reductions. An example of the application of MACC assessments to crop and soils in the UK can be seen in MacLeod et al, (2010).

This paper describes the framework adopted to calculate the abatement potential of a short listed range of abatement options that could be applied in the livestock sector and estimate their relevant cost effectiveness. This allows for a comparison of options, looking at the amount of GHG they abate and how much they cost to implement. Although results are presented for a range of livestock mitigation options this study focuses on estimating the cost effectiveness of a range of genetic improvement options in beef and dairy cattle.

## Materials and Methods

**Prioritization of abatement options** A detailed review of the literature highlighted a vast array of abatement options from the livestock industry, which fell into two broad categories, those options that focus on animal management options and those that focus on manure management. These options were reviewed and ranked on their likely uptake and feasibility in over 3 time points. These time points were 2012, 2017 and 2022 and are related to points at which the UK government will review progress to emissions reduction. Certain options were considered similar in mode of action and likely outcome, and were therefore reduced to a single option. Options that included a simple reduction in animal numbers and/or product output, above and beyond those assumed by the business as usual (BAU) scenario, were also eliminated as there is a need to avoid displacing domestic demand overseas. Livestock land management options (e.g., spreading of manures to crop/grassland) were not included in this study although represented in other studies (e.g., MacLeod et al., 2010). The abatement options explored can be summarized by four main categories of abatement options:

1. Diet modification and dietary supplementation
2. Genetic improvement and technologies
3. Manure management options
4. Anaerobic digestion

### Estimating the abatement potential and cost-effectiveness of mitigation options from livestock

Information on the abatement potential of each option was reviewed and effects summarized from available literature. There have been many studies examining various abatement options, examining different aspects of their application, efficacy and/or cost effectiveness and some base assumptions were taken from a previous study on cost curve assessment of mitigation options (IGER, 2001). A wider literature review was also conducted to ensure that the estimates fell within other studies which were generally consistent between studies. However, with some options there were differences in the reported effects due to differences in experimental protocol, site effects, dose effects, animal variation, which means that the range can be far wider than for more established and widely studied methods.

The input information required for each abatement option included the efficiency of the abatement options (e.g., reduction on $CH_4$ per animal), the applicability (the maximum percentage of animals to which the abatement options could be applied), the effect on productivity, if any (e.g., percentage dis/improvement in production with the application of the abatement options), and/or the effect on feed intake. Other input data included adoption rates, animal numbers from BAU scenarios published by the UK government, IPCC emission factors, manure storage capacities and proportions of manure handled in different systems, efficiency data for anaerobic digestion plants, lifetimes of each measure and relevant cost data.

A productivity effect was applied when dealing with dairy animal abatement options, in that it was assumed an improvement in dairy yield would result in a reduction in the total number of animals under a quota scenario. The converse was also true such that is an abatement options reduced production (mode of action was directly on reducing methane emissions) then the number of dairy cows would increase to obtain the previous level of milk output. This was only applied in the dairy scenario. For beef it was assumed that producers would increase production output if output were improved with a particular abatement option. The calculation of abatement potential and associated costs was detailed in the spreadsheet to ensure that changes to the expected impact of an option would update results automatically. The list of livestock animal measures is given in Table 1.

**Table 1. Description of the “direct” and “indirect” costs associated with dairy animal abatement measures**

| | Direct | Indirect | Notes |
|---|---|---|---|
| Concentrate | Switching to higher concentrate content in the diet | Fewer animals to maintain through the year | Concentrate cost linked to cereal price forecast |
| Maize silage | Switching maize for grass silage | “” | |
| Propionate | Annual admin cost | “” | |
| Probiotics | Annual admin cost | “” | |
| Ionophores | Annual admin cost | “” | |
| Bovine Somatotropin | Annual admin cost | “” | |
| Genetic improvement in production traits | Free[*] | “” | |
| Genetic improvement in fertility traits | Free | “” | |
| Transgenic offspring | Estimated cost offspring of transgenic parents | “” | Capital cost with lifetime of 5 years |

*Scenario modelled with costs of recording feed efficiency traits and it’s direct inclusion in the breeding goal also modelled.

The cost of implementing each animal management abatement option was estimated using the annual cost of administering the abatement option per treated animal and multiplied by the number of animals treated. The costs of the nutrition options (e.g., increasing proportion of maize silage) accounted for the number of days that the abatement option would be administered and change in the cost of the diet compared to previous options. For dairy cattle, the cost-effectiveness also accounted for the reduction in overall annual costs by reducing the cow herd size at a fixed level of output if the abatement option improved productivity. The animal numbers for current and the future time points were taken from mapped BAU livestock numbers. The baseline annual $CH_4$ emissions (enteric fermentation and manure) from a particular livestock industry were calculated using IPCC Tier 1 methodologies. For beef cattle the cost of implementing an abatement option considered the direct costs of application of the options as well as any indirect benefit that may accrue from increased production output through increase volume of meat sales. Costs were considered at 2006 prices (adjusted from reported values). The costs of the manure management options were calculated by estimating the investment required to implement the measure and the associated annual running cost per storage unit. The numbers of storage units was estimated from the proportion of manure volume and from the average storage capacities in each manure management system.

The livestock options were developed using the BAU estimates of livestock numbers such that each measure was applied to the number of livestock in 2012, 2017 and 2022. The assumed technical potential and feasibility levels for livestock and manure management options were derived based on statistics on uptake and compliance rates of other agricultural initiatives/incentives. The uptake/compliance rates were applied based on costs for each abatement option (i.e., positive or negative) and if the measure was assumed to be difficult or easy to enforce. Some of the livestock measures may never be applicable in all livestock systems (e.g., use of feed additives is unlikely to become allowable in organic herds). This is not reflected in the uptake/compliance rates per say but it was assumed that these abatement options were only applicable to a proportion of the livestock population (e.g., 90% applicability of bovine somatotropin in dairy). Uptake levels for anaerobic digestion options are set for central, high and low feasible potentials for 2022 at 45%, 75% and 30%, respectively. For 2008 0% uptake was assumed, and for the years in between the same linear adoption function was set up to calculate the uptake rates as was used for other livestock options.

Each of the abatement potentials and their cost-effectiveness was first studied on a stand-alone basis. However, it is unlikely that all measures studied will work effectively together (e.g., there is no way of applying a manure management strategy such as covering tanks if central or on farm anaerobic digestion is taking place). On the other hand some of the abatement options may be complementary and can be applied simultaneously (e.g., genetic improvement and dietary modifications). There has been little work done on the effects of combined measures in livestock systems. Therefore in this study interactions between livestock measures were assumed to be either 0 or 1, such that 0 meant that the pair wise combination of measures could not be applied simultaneously and 1 meant that measures could be applied simultaneously and the effects could be additive.

## Genetic improvement and technologies

Generally, genetic improvement for production efficiency in livestock species will help to reduce GHG emissions. In many cases this can be achieved simply through selection on production traits and traits related to the efficiency of the entire production system (e.g., fertility and longevity traits). The impact of selection on these traits is two-fold. Firstly, reducing the number of animals required to produce a fixed level of output: There has been an overall reduction of annual methane emissions (28% from 1990 to 1999) in the UK economy. The reduction in methane emissions from agriculture, as represented in the national inventory reporting systems, has been low (4%) and can mainly be attributed to a decrease in cattle numbers due to increased productivity in dairy cows (Defra, 2001). The dairy sector in Canada has reduced its methane emissions by 10% since 1990 also by reducing the number of animals (Désilets, 2006). Secondly, increasing the efficiency of production will help reduce the finishing period for meat animals, therefore reducing emissions per unit output. Hyslop (2003) demonstrated that efficiency of the beef production system was paramount in reducing the GHG emissions/unit output showing that intensive concentrate based systems produce the lowest emissions (note: this study did not consider the externalities of the system such as the carbon cost of producing concentrate diets). Further analyses of the data showed that there was also a significant breed difference suggesting that bigger continental breeds of cattle produced less emissions/unit output than the smaller British type breeds (Hyslop, 2003).

The study of Jones et al. (2008) used a Life Cycle Analysis approach, as developed by Williams et al. (2006), to estimate the impact of historic genetic improvement in production traits (e.g. milk/meat output, growth efficiency) in UK livestock species on the GHG emissions from the production of the relevant agricultural commodity (e.g., a ton of beef/sheep meat). On average, there was a 1% per year reduction in GHG production per unit food produced that could be attributed to genetic improvement. The reduction was shown to be greatest in those species with more widespread use of genetic improvement such as layer hens, broiler chickens, pigs and dairy cattle. However, the reductions were a great deal smaller in beef cattle and sheep. This was due to poorer rates of genetic improvement across the population in these sectors and poor dissemination of information from elite breeders to the commercial populations in the UK context. A range of genetic improvement tools that could abate GHG in dairy and beef animals were studied.

**Genetic improvement in dairy: production** The first genetic improvement option in dairy focused on current conventional genetic improvement whereby milk production is expected to improve at a rate of 1.5% per annum (Simm, 1998). As genetic improvement, if carried out consistently, will lead to permanent and cumulative change in the population, it was assumed that production would continue to improve at a rate of 1.5% per annum with no associated effect on $CH_4$ emissions. The method applied in the overall framework of examining abatement potential from dairy, accounted for a reduction in animal numbers with an improvement in milk production per cow. This will partly take account of some of the wider life cycle issues when examining the potential of genetic improvement.

**Genetic improvement in dairy: fertility** A second option for genetic improvement in dairy was considered, this time considering a shift in the emphasis of

**Table 2. Livestock Measures Central Feasible Potential for 2012, 2017 and 2022, discount rate: 3.5%.**

| | 2012 | | 2017 | | 2022 | | |
|---|---|---|---|---|---|---|---|
| Options | Gross vol. abated (annual, kt $CO_2$e) | Cost effectiveness (£/t $CO_2$e) | Gross vol. abated (annual, kt $CO_2$e) | Cost effectiveness (£/t $CO_2$e) | Gross vol. abated (annual, kt $CO_2$e) | Cost effectiveness (£/t $CO_2$e) | Cumulative abatement (annual, Mt $CO_2$e) |
| Ionophores (beef) | 103.39 | -1,384.37 | 227.68 | -1,556.29 | 347.38 | -1,747.79 | 0.347 |
| Genetic improvement (beef) | 4.60 | -2,873.75 | 20.26 | -3,217.28 | 46.32 | -3,602.93 | 0.394 |
| Genetic impr (beef, RFI + carcass) | -16.13 | -74.26 | -51.84 | -52.94 | -64.79 | -37.74 | 0.648 |
| Ionophores (dairy) | 215.77 | -49.99 | 174.13 | -0.07 | 377.36 | -0.07 | 0.771 |
| Maize Silage (dairy) | 27.99 | -270.22 | 480.61 | -49.28 | 739.66 | -48.59 | 1.511 |
| Genetic improvement: production (dairy) | 41.82 | -0.07 | 62.39 | -266.23 | 346.26 | -0.04 | 1.857 |
| Genetic improvement: fertility (dairy) | 33.38 | -0.04 | 160.70 | -0.04 | 95.98 | -262.63 | 1.953 |
| OFAD: large farms (beef) | 27.47 | 3.36 | 62.35 | 3.33 | 47.77 | 0.96 | 2.001 |
| OFAD: large farms (pigs) | 14.18 | 6.63 | 31.45 | 3.82 | 97.79 | 2.52 | 2.099 |
| CAD: 5MW (poultry) | 61.36 | 9.43 | 10.58 | 8.14 | 16.06 | 4.69 | 2.115 |
| OFAD: medium farms (pigs) | 4.77 | 11.67 | 154.53 | 10.60 | 250.81 | 7.96 | 2.365 |
| OFAD: large farms (dairy) | 64.19 | 13.63 | 139.15 | 10.80 | 219.34 | 11.43 | 2.585 |
| OFAD: medium farms (beef) | 15.56 | 18.33 | 33.80 | 18.07 | 50.77 | 16.96 | 2.635 |
| OFAD: medium farms (dairy) | 20.76 | 26.12 | 36.40 | 25.53 | 44.12 | 24.10 | 2.680 |
| Bovine somatatrphin (dairy) | 38.60 | 230.48 | 86.00 | 227.17 | 132.31 | 224.10 | 2.812 |
| Offspring of transgenic animals (dairy) | 147.13 | 1,739.62 | 327.68 | 1,715.14 | 504.29 | 1,691.28 | 3.316 |
| Increase dietary concentrates (beef) | 24.12 | 2,110.15 | 53.11 | 2,394.58 | 80.96 | 2,704.54 | 3.397 |

*OFAD: On farm anaerobic digestion
*CAD: Central anaerobic digestion

the national breeding goal from dairy cows to select animals with improved fertility. The study of Garnsworthy (2004) showed that if fertility was returned its level in 1995 enteric methane emissions from the milking herd would be reduced 11%. Using the results of Wall et al (2007) an index that would bring about this improvement in fertility over a 10 year period would result in a halving of the rate of improvement in milk production. The impact of such a change of selection emphasis in UK dairy cattle was modeled.

**Genetic improvement in beef** As discussed earlier, the study of Jones et al. (2008) showed the potential impact of genetic improvement on overall GHG emissions within the sections of the national beef herd that adopts genetic improvement on data recording. The potential of the beef industry to reach this reduction is limited by the low uptake and use of genetic indices and data recording across the whole population. The impact of increasing the use of genetic improvement across a wider proportion of the national beef herd was modeled by examining the difference between current low rates of uptake (10%) to a higher rate of uptake (50%). These values were simplified, with expert guidance, from the study of Amer et al. (2007). In addition, to the improved uptake of "traditional" (to the UK) genetic improvement tools in beef, the impact of recording feed efficiency routinely on a small proportion of the pedigree informative population was also explored such that a higher rate of genetic improvement for feed efficiency traits could be achieved via direct selection, rather than a correlated change. Further improvements to the trait recording by direct selection on carcass trait attributes were also examined.

The costs of the majority of genetic improvement tools was deemed to be zero as these tools are currently developed, or could be easily developed, and ongoing implementation costs covered by the established genetic improvement provision costs (e.g., levy contribution and other supported funds). In the case of feed efficiency, the costs for the routine provision of data recording for feed efficiency on approx. 1000 animals a year was included in the cost-benefit analysis.

**Use of offspring of "genetically modified" individuals.** Taking a longer term view of potential abatement options, it is possible to envisage that genetically modified livestock may be developed with desirable trait characteristics, one of which may include increased feed efficiency and therefore reduced greenhouse gas emissions. This scenario is highly speculative. It was assumed that directly genetically modified animals would not be used routinely in production of livestock products (meat and milk). However, the offspring of genetically modified animals (e.g., genome editing), via the use of semen and/or embryos of genetically modified animals, may have some potential applicability to the production of livestock products. It was assumed that the offspring of animal(s) genetically modified would be more efficient and would produce 20% less $CH_4$ and 10% more milk. The cost of administration was estimated based on the current value of a high genetic merit dairy animal. This option was examined for dairy only.

## Results and Discussion

Table 2 summarizes the abatement potentials for the three time periods (2012, 2017 and 2022) for the central feasibility set of assumptions including the abatement potential and cost effectiveness of the options remaining after interactions were consider across the three time points and the cumulative abatement of the options in 2022. The cost effective potential in 2022 were estimated to range from 1.27 - 5.02Mt$CO_2$e, i.e. an annual abatement in this range could be achieved by the livestock sector at a cost of <=£26.50/t by 2022. The central feasible potential of 2.68 Mt$CO_2$e represents around 5 % of the 2006 UK agricultural GHG emissions (estimated as 44.12 Mt$CO_2$e, excluding land use change by Choudrie et al., 2008).

After interactions between the options had been accounted for the abatement options for livestock included the use of ionophores in beef and dairy feed, all genetic improvement options in beef and dairy animals, increasing the proportion of maize silage in beef diets, on farm anaerobic digestion on medium or large beef, dairy and pig farms and central anaerobic digestion for poultry systems. Some options were extremely cost inefficient including the use of bovine somatotropin in dairy animals, using the offspring of genetically modified dairy animals and increasing dietary concentrates in beef diets. This is, in part, due to the cost of implementing such options, compared to current practices. Many of the manure management options dropped out of the final list once interactions were considered due to the efficiencies seen with AD and given that AD and manure management options were considered not to interact (i.e., a farm couldn’t change the manure storage and put it through anaerobic digestion at the same time).

The results show that a range of options, both animal and manure management options, show high potential for the abatement of GHG from livestock systems. However, it should be noted that some options are currently prohibited by EU law such as the use of ionophores as a feed additive in livestock rations. The addition of ionophores in the diets of livestock is not prohibited elsewhere in the world (e.g., USA). In the future it could become an option in the EU, particularly if proven to be an effective abatement tool. It should also be noted that reported effects, particularly long term, of the use of ionophores can vary. To ensure the effects of ionophores are consistent in UK livestock systems it would be necessary to study their effect in practice and in commercial livestock systems over the longer term.

Some of the top abatement options that proved cost effective where in the beef sector. This can be expected given the range of efficiencies in UK beef systems ranging from low input extensive grazing based systems with animals reaching final slaughter weight at 2 years or move to high input grain based systems with systems with animals reaching final slaughter weight at 1 year or less. Also, in beef sector, as described earlier, the use of recording and genetic selection tools means the productivity improvements experienced in the systems that utilize these tools is not as widespread as in other livestock sectors (e.g., dairy, pig, and poultry). The uptake of such tools and increasing production efficiency in some beef systems will have a large impact on overall GHG emissions but will also have an impact on the overall farm profit and sustainability.

Each of the livestock abatement measures examined have been researched and based on published results. However, there have been limited studies on the long term effects of the many of the abatement options in a range of systems. This is particularly the case for the nutritional management options (e.g., feed additives) and there tends to be a range of the abatement potentials. Factors that may influence the abatement potential of a particular option include variations between animals and management factors. Also, few studies have examined the impact on other aspects of the system, for example the impact on manure quality and it's efficacy when used as an organic fertilizer. It may be necessary to further examine the impact of system type on the efficacy of different measures and refine the MACC accordingly.

In general, only a proportion of the options would be considered and measured in the current UK national inventory of greenhouse gases. However, for some of the measures a proportion of the abatement potential would be reflected in the inventory as currently practiced. For example, the abatement potential of various animal management interventions was examined for dairy animals and their systems. These included nutritional and genetic improvement interventions to reduce GHG emissions. The assumptions in estimating the abatement potential from dairy systems assumed that milk quotas would still be operational into the future and therefore if an abatement measure improved production then the number of animals required to meet the national quota would reduce. These measures would be reflected, in part in the national GHG inventory. However, many of the dairy options have an additional GHG reducing effect, in that they reduce overall $CH_4$ output and this effect would not be accounted for the UK inventory.

## Conclusion

The paper has focused on the direct economic costs and benefits to producers of each abatement option to determine their cost effectiveness. However, it is likely that further ancillary or external costs and benefits could arise that do not directly affect producers. These costs or benefits could either accrue to other sectors (where they could take the form of increased GHG emissions) or society as a whole. Ancillary benefits (and costs) could be quantified and incorporated into the overall cost effectiveness of each abatement option using various valuation methods. Some of the less tangible ancillary effects such as the public acceptance of livestock measures (e.g., the use of offspring of genetically modified animals) may prove harder to value. However, these values may, in practice, be revealed in changes in demand for products where such measures have been applied. This is a potentially important market effect that could present a barrier to uptake of some measures. All genetic improvement options studied, including the establishment of direct recording of feed efficiency in beef, proved to be cost effective option for reducing greenhouse gas emissions in the short, medium and longer term. Moreover, genetic improvement has little additional costs once systems have been established and impacts are cumulative and therefore is a highly sustainable option for ongoing reductions in GHG emissions

## Acknowledgements

The Rural and Environmental Research and Analysis Directorate and the UK Committee for Climate Change are gratefully acknowledged for supporting this work. Many thanks to colleagues for providing expert input into the development of this work including Michael MacLeod, Bob Rees, Geoff Simm and Kairsty Topp. Jenny Byars and Mike Thomson provided continuous and insightful steering of this work. SRUC received funding from the Scottish Government.

## Literature Cited

Amer, P. R., G. J. Nieuwhof, G. E. Pollott, et al (2007). Animal, 1: 1414-1426.

Choudrie S.L., J. Jackson, J.D. Watterson, et al (2008). UK Greenhouse Gas Inventory, 1990 to 2006.

Defra, (2001). 3rd National Communication to UNFCCC.

Désilets, E., 2006. Greenhouse gas mitigation program from Canadian Agriculture.

Garnsworthy, P.C (2004) Anim Feed Sc & Tech 112; 211-223.

IGER, 2001. Cost curve assessment of mitigation options in greenhouse gas emissions from agriculture.

Jones, H.E., C.C. Warkup, A. Williams and E. Audsley (2008). Proc. EAAP, Vilnius, Lithuania, August 2008.

MacLeod, M, D. Moran, V. Eory, et al. (2010). Agric Syst. 103: 198-209

Moss, A.R., J.P. Jouany and J. Newbold (2000). Annales de Zootechnie, 49: 231-253.

Simm, G. 1998. In Genetic Improvement of Cattle and Sheep. Published by Farming Press. Ipswich UK.

Smith, P., Martino, D., Cai, Z., et al (2008). Phil Trans of Royal Soc B: Biol Sc, 363(1492), 789-813.

Steinfeld, H., Gerber, P., Wassenaar, T. D., et al (2006). Livestock's long shadow: environmental issues and options. FAO

Wall, E., M.P. Coffey & S. Brotherstone (2007). Developing a robustness index for UK dairy cows. Proc. BSAS 2007. Abstract No. 52.

Williams, A.G., E. Audsley and D.L. Sandars (2006). Final report to Defra on project ISO205.