Greenhouse gas emissions from contrasting beef production systems

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Declaration

I declare that I have composed the present thesis. This is my own work and assistance has been duly acknowledged. The work described has not been submitted for any other degree or professional qualification.

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Abstract

Agriculture has been reported to contribute a significant amount of greenhouse gases to the atmosphere among other anthropogenic activities. With still more than 870 million people in the world suffering from under-nutrition and a growing global food demand, it is relevant to study ways for mitigating the environmental impact of food production. The objective of this work was to identify gaps in the knowledge regarding the main factors affecting greenhouse gas (GHG) emissions from beef farming systems, to reduce the uncertainty on carbon footprint predictions, and to study the relative importance of mitigation options at the system level.

A lack of information in the literature was identified regarding the quantification of the relevant animal characteristics of extensive beef systems that can impact on methane (CH_4) outputs. In a meta-analysis study, it was observed that the combination of physiological stage and type of diet improved the accuracy of CH_4 emission rate predictions. Furthermore, when applied to a system analysis, improved equations to predict CH_4 from ruminants under different physiological stages and diet types reduced the uncertainty of whole-farm enteric CH_4 predictions by up to 7% over a year. In a modelling study, it was demonstrated that variations in grazing behaviour and grazing choice have a potentially large impact upon CH_4 emissions, which are not normally mentioned within carbon budget calculations at either local or national scale. Methane estimations were highly sensitive to changes in quality of the diet, highlighting the importance of considering animal selectivity on carbon budgets of heterogeneous grasslands. Part of the difficulties on collecting reliable information from grazing cattle is due to some limitations of available techniques to perform CH_4 emission measurements. Thus, the potential use of a Laser Methane Detector (LMD) for remote sensing of CH_4 emissions from ruminants was evaluated. A data analysis method was developed for the LMD outputs. The use of a novel technique to assess CH_4 production from ruminants showed very good correlations with independent measurements in respiration chambers. Moreover, the use of this highly sensitive technique demonstrates that there is more variability associated with the pattern of CH_4 emissions which cannot be explained by the feed nutritional value. Lastly, previous findings were included in a deterministic model to simulate alternative management options applied to upland beef farming systems. The success of the suggested management technologies to mitigate GHG emissions depends on the characteristics of the farms and management previously adopted. Systems with high proportion of their land unsuitable for cropping but with an efficient use of land had low and more certain GHG emissions, high human-edible returns, and small opportunities to further reduce their carbon footprint per unit of product without affecting food production, potential biodiversity conservation and the livelihood of the region. Altogether, this work helps to reduce the uncertainty of GHG predictions from beef farming systems and highlights the essential role of studies with a holistic approach to issues related to climate change that encompass the analysis of a large range of situations and management alternatives.

Publications

Research articles (peer-reviewed)

Ricci, P., Rooke, J., Nevison, I., Waterhouse, A. 2013. Methane emissions from beef and dairy cattle: quantifying the effect of physiological stage and diet characteristics. Journal of Animal Science, 91:5379-5389.

Ricci, P., Umstätter, C., Holland, J. P., Waterhouse, A. 2014. Does diverse grazing behavior of suckler cows have an impact on predicted methane emissions? Journal of Animal Science, 92:1234-1244.

Ricci, P., Duthie, C-A., Hyslop, J., Houdijk, J., Roehe, R., Rooke, J., Waterhouse, A. Methane emissions from ewes and steers measured with the Laser Methane Detector are correlated with respiration chamber measures. Article submitted for publication in Journal of Animal Science.

Conference abstracts (peer-reviewed)

Ricci, P., Wilson, R., Hyslop, J., Johnson, S., Rees, R. and Waterhouse, A. **2013**. Beef systems of varying intensity and land use have different rankings in terms of carbon and food output metrics. Abstract submitted to the conference: Sustainable intensification: the pathway to low carbon farming? 25-27 September, 2013, Edinburgh, UK.

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Ricci, P. and Waterhouse, A. **2011**. Predicting methane emissions from beef cattle on different grasslands – does the prediction equation matter? Advances in Animal Biosciences, 2:79.

List of abbreviations

°C	Degrees Celsius
A	Aberdeen Angus
ADF	Acid Detergent Fibre
$AdjR^2$	Adjusted coefficient of determination
AFRC	Agricultural and Food Research Council
AL	*ad libitum*
AxL	Aberdeen Angus cross Limousin
BW	Body weight
BWC	Body weight change
C	Carbon
CAST	Council for Agricultural Science and Technology
C_b	Bias correction factor
CCC	Concordance Correlation Coefficient
CH_4	Methane
CH_4pair	Methane output of cow-calf pair
CHA	Charolais
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents
CP	Crude Protein
CPF	Cumulative Probability Function
DE	Digestible Energy
DEFRA	Department for Environment, Food and Rural Affairs
DEI	Digestible Energy Intake
DM	Dry Matter
DMD	Dry Matter Digestibility
DMI	Dry Matter Intake
e.g.	*exempli gratia*
FAO	Food and Agriculture Organization of the United Nations
FP	Forage Proportion
g	Gram(mes)
g/d	Gram(mes) per day
GDP	Gross Domestic Product
GE	Gross Energy
GEI	Gross Energy Intake
GHG	Greenhouse Gas(es)
GPS	Global Positioning System
GWP	Global Warming Potential
h	hour(s)
H_2	Hydrogen
Ha	Hectare(s)
HC	High-concentrate diet
HG	Hill grassland
i.e.	*id est*

IPCC	Intergovernmental Panel on Climate Change
Kg	kilogram(mes)
L	Limousin
LC	Low-concentrate diet
LG	Lowland grassland
LMD	Laser Methane Detector
LUI	Luing
LxA	Limousin cross Aberdeen Angus
m	metre(s)
MBW	Metabolic body weight
ME	Metabolisable Energy
MeanResp	Mean respiration time
MEI	Metabolisable Energy Intake
min	minute(s)
MJ	Mega Joule(s)
Mt	Mega ton(nes)
N	Nitrogen
n	Number of observations
N_2	Di-nitrogen
N_2O	Nitrous oxide
NDF	Neutral Detergent Fibre
NewEqDMI	New Equations based on DMI
NewEqGEI	New Equations based on GEI
NewEqs	New Equations developed in Chapter 2
NRC	National Research Council
OM	Organic Matter
P1 to P5	Periods of observation 1 to 5
ppm	Part(s) per million
r	Pearson correlation coefficient
RBU	Rural Business Unit, SAC
RES	Restricted intake
RFI	Residual Feed Intake
SAC	Scottish Agricultural College
SACs	Special Areas of Conservation
SAS	Statistical Analysis System
SD	Standard Deviation
SE	Standard Error
SEC	Standard Error of the Calibration
sec	Second(s)
SEV	Standard Error of the Validation
SF_6	Sulphur hexafluoride
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SRUC	Scotland’s Rural College
SSSIs	Special Sites of Scientific Importance

Treat	Treatment
U.S.EPA	United States of America - Environmental Protection Agency
UK	United Kingdom of Great Britain and Northern Ireland
UNFCCC	United Nations Framework Convention on Climate Change
VFA	Volatile Fatty Acids
vs.	*versus*
Ym	Methane emission factor
yr	Year(s)
µm	Micrometre(s)

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Chapter 1: General introduction

There is no doubt that the climate is changing. In 2007, the Intergovernmental Panel on Climate Change (IPCC) stated that the *"warming of the climate system is unequivocal"* (IPCC, 2007b). Considerable evidence is available demonstrating that increases in temperature are affecting natural systems. For instance, ocean acidification is having devastating effects on marine environments and changes of climate cycles are causing extreme weather events with increased severity and occurrence. Moreover, "emerging effects" in human and natural environments could have potential impacts on human health, agricultural and forestry management and other human activities (IPCC, 2007b).

These changes have been attributed to the rise in emissions of "long-lived" greenhouse gases (GHG) into the atmosphere (IPCC, 2007c). This increase has been documented to be 70% in 34 years (from 1970 to 2004). The main reasons for this increase of GHG are anthropogenic activities, such as increased demands for energy supply, transport and industrialization, followed by commercial and residential buildings, deforestation (land-use change), and agriculture.

Globally, agriculture is reported to produce 13.5% of the total GHG emissions (IPCC, 2007d). Within the agricultural sector, livestock production has been reported to be responsible for between 8 and 10.8% of the total GHG emissions (O'Mara, 2011), and the cause of land degradation, air and water pollution, and loss of biodiversity (Steinfeld et al., 2006). Official figures show that agriculture in the UK contributes 7% of the total UK greenhouse gas emissions, 38% of methane (CH_4) and 73% of nitrous oxide (N_2O) emissions (CCC, 2010).

There is a need to reduce global GHG emissions in order to avoid further rises of the temperature of the planet (CCC, 2010). Although the 7% contribution from agriculture to total emissions in the UK seems not to be significant, Scotland has established an ambitious target of reducing by 42% their total emissions recorded in 1992 by 2020 and 80% by 2050 (Scottish Government, 2008). Moreover, the recent report of the USEPA (2013) confirmed that enteric fermentation is still the second source of CH_4 and agricultural soil management the first source of N_2O emissions.

Therefore, it is critical that every sector contributes towards reducing its own carbon (C) emissions.

Agriculture, and beef production in particular, has been under debate due to their important role of producing food for human consumption.

> *"(...) Agriculture in the 21st century faces multiple challenges: it has to produce more food and fibre to feed a growing population with a smaller rural labour force, more feedstocks for a potentially huge bioenergy market, contribute to overall development in the many agriculture-dependent developing countries, adopt more efficient and sustainable production methods and adapt to climate change (...)"*
>
> *(FAO, 2009)*

Therefore, it is critical to review the role of livestock systems and to understand how GHG emissions from this sector can be mitigated in order to maintain sustainable food production systems. The objective of this introductory chapter is to review the literature related to GHG emissions from beef production systems and identify gaps in the knowledge that should be investigated further. Different contributors to emissions and sinks of GHGs from agricultural systems will be described, followed by management activities studied for their mitigation. While the literature regarding all GHGs from agriculture has been reviewed, this thesis will be more focused on issues related to CH_4 emissions. Available methodologies for CH_4 measurement and modelling approaches will be reviewed and their suitability to represent the natural diversity of production systems will be discussed. Finally, important sources of uncertainty for GHG quantification will be outlined and the objectives of this thesis defined.

1.1 Food production, economic and biodiversity sustainability

Ruminant livestock production systems are considered one of the most important economic sectors in the world. The worldwide importance of this sector is reflected by the 70% of the agricultural area of the world consisting of grasslands (FAO, 2010), which represents the major area of many countries. Most of this grassland area is classified as unimproved rangeland, where natural conditions do not allow crop productions (Lund, 2009). Instead, ruminants are able to convert grasslands and poor rangelands into high quality food such as meat and milk for human consumption and raw material for other industries, for instance wool, fleece and leather, among other animal products. Moreover, they also have the advantage of converting by-products and wastes from other industries into animal products, which otherwise would be incompatible for other purposes (Oltjen and Beckett, 1996; Garnett, 2009). From a socio-economical point of view livestock production in many regions helps to sustain livelihoods in remote areas (CAST, 1999; Reid et al., 2004). Consequently, livestock production plays a vital role, contributing towards reducing poverty and malnutrition in many countries that have bio-physical constraints for arable land; livestock provides either food or animals by-product for purchasing more food (FAO, 2012).

Agricultural systems are of particular economic importance in Scotland, where livestock production systems represent 60% of agricultural output (Scottish Government, 2009). The area of grassland in Scotland represents 82.4% of the total agricultural area and more than 70% of that area is classified as rough land. Moreover, 85% of the land is classified as less favoured area much of which is unsuitable for cropping (Scottish Government, 2009). Comparisons with other countries show agriculture as a more important industry, both in terms of Gross Domestic Product (GDP) and in its extent, and thus the problem of GHG emissions seems to be more critical. For instance, in Argentina, agriculture represents 32% of GDP with 50 and 13 million head of cattle and sheep, respectively (UNFCCC, 2007). Argentinian agriculture has suffered profound changes in the past decades, and the cultivated area has increased by 45% from 1999 to 2006 (Aizen et al., 2009). However, only 12% of the terrestrial land of the country is suitable for crop production. The same proportion of the land is covered by forests and 36.5% is grasslands. These numbers highlight the importance of the agricultural sector from a socio-economic point of view. Although, the total net emissions of carbon dioxide

(CO_2) equivalents in Argentina were reported to be 84 Mt in 2000 (UNFCCC, 2007), which are much lower than the 574 Mt total emissions in the UK (CCC, 2010), GHG emissions from agriculture in Argentina represent 44.3% of its total emissions (UNFCCC, 2007).

In addition to the role of livestock for food production, foraging of grasslands by domestic herbivores helps to maintain the indigenous flora and fauna of these habitats (Peeters, 2009; Papanastasis, 2009; Rosa García et al., 2013). Ruminants have evolved and adapted anatomically to utilise high-cellulose diets (Van Soest, 1996) and grasslands have evolved and adapted to grazing animals (Strömberg, 2011). Many of these grasslands have high biodiversity and are highly valued for their wildlife. However the inadequate utilization of these grasslands by either over and/or under-grazing has caused the loss of invaluable species and soil erosion. This impact is potentially irreversible depending on the intensity of the damage caused (Li et al., 2013; Rosa García et al., 2013). Areas containing habitats that are recognised by designated areas at a UK level (Sites of Special Scientific Interest, SSSIs) and at European level (Special Areas of Conservation, SACs) for a wide range of vegetation species are maintained by appropriate grazing regimes. In Scotland, SSSIs cover more than 1 million ha (SNH, 2012) and in the UK, SACs cover 2.7 million ha (JNCC, 2012). Upland grazing areas have important habitats and have large areas with legal requirements for protection aimed at preventing their loss, and improving their condition. In these areas the sustainable grazing management of various ruminants (e.g. cattle, sheep and deer) is needed to preserve the balance of species in the grassland and their diversity. Thus, changes in policy to reduce GHGs must also take into account these conservation management objectives alongside economic objectives.

From a GHG emissions perspective, reducing the number of ruminants on grasslands would be the way to decrease emission levels quickly. However, non-grazing activity will have a negative effect on the biodiversity of a given grassland by affecting the floristic balance of semi-natural grasslands, giving the opportunity to more invasive plants co-existing in the same area or community of plants to win the battle for resources (light, water, and nutrients) against other species (Alonso et al., 2001). It has been demonstrated that grazing a heterogeneous grassland helped to reduce the more invasive species and increase the green material in the biomass (Fraser et al., 2011). The action of the grazing activity on the balance of species within grasslands differs between species of animals. Bovines in particular are less selective than small ruminants, such as sheep (Fraser et al., 2009) which would help to conserve the floristic biodiversity of the grassland by reducing the competition between species and maintaining the canopy at a similar level. The turnover of plant biomass into large amounts of animal faeces creates a whole segment of the ecosystem with coprophagous invertebrate communities (Nichols et al., 2008) and wildlife that depends upon them (Vickery et al., 2001). Hence grazing herbivores provide an important source of food as live prey for highly valued species of birds. An adequate stocking rate is needed to achieve the conservationist activity of grazing animals. In other words an excessive "grazing pressure" could have an irreversible negative impact on the balance of grassland species. Over-grazing as a result of high stocking rates allows some species to grow better than others, while the more delicate ones disappear due to excessive grazing pressure or unwanted trampling and destruction of the soil (Rosa García et al., 2013).

If degraded grassland has not reached the point of irreversible damage (e.g. impacts on abiotic components such as soil erosion) there is opportunity for grasslands to be restored through the utilization of well managed grazers (Papanastasis, 2009). Examples in Scotland are the use of flying sheep flocks to maintain SSSIs promoted by the Scottish Wildlife Trust and the conservation cattle grazing project carried out by the Forestry Commision Scotland. These examples illustrate why the preservation of well-managed grazing animals in equilibrium with grassland management is important to preserve these unique environments. Although it has been demonstrated that a well-managed natural grassland allows extra C sequestration compared with an unmanaged grassland (Derner and Schuman, 2007) there is still a lack of understanding of the relationship between biodiversity and GHG emissions.

Reducing the number of cattle in the attempt to reduce GHGs will also have an impact on food security, especially in areas where no other food can be produced. Consequently, the study of GHGs from a holistic point of view is relevant to understanding how different management alternatives can be applied under different farming situations and understanding the GHG mitigation potential of diverse types of livestock systems without affecting their important role of converting grass into human food in a sustainable way.

1.2 Greenhouse gas emissions from agriculture

There are large uncertainties in the available methodologies for GHG accounting (IPCC, 2006) used world-wide, thus it is critical to review the literature and investigate potential improvements for their prediction. There are 1.35 billion cattle in the world and this number is likely to rise, driven by a growing global demand for animal products (O'Mara, 2011). Therefore, understanding how GHG emissions occur in beef farming systems and how they might be reduced is essential to study the GHG mitigation potential from beef production systems.

The main GHGs exchanged in agricultural systems are CO_2, N_2O and CH_4. The impact of each gas in the atmosphere is different from the amount produced since they have a different global warming potential (GWP); N_2O has been calculated to have 298 times the GWP of CO_2, while CH_4 has 25 times that of CO_2 over a 100 year period (IPCC, 2007a). Diverse sources of GHG emissions and fixation can be identified in a beef production system (Figure 1). Carbon dioxide is mainly produced by soil microbes and plant and animal respiration affected by soil management, grazing type, organic and inorganic fertilisers, and drainage. Changes in C stock from managed soils, the use of fossil fuel from machinery, lime and urea application, and prescribed fire add more CO_2 emissions. The current methodology proposed by IPCC (2006) accounts for CO_2 emissions from agricultural related activities, but does not considers CO_2 emissions from plant and animal respiration as it assumes that these emissions are counteracted by the CO_2 fixed by photosynthesis. Sources of N_2O are mainly nitrogen (N) loss from fertilisers and manure applications, and manure handling and storage (Oenema et al., 1997; Smith and Conen, 2004). Finally, CH_4 is produced mainly from the enteric fermentation of ruminants and a fifth of the amount emitted from enteric fermentation is emitted from their manure (Steinfeld et al., 2006).

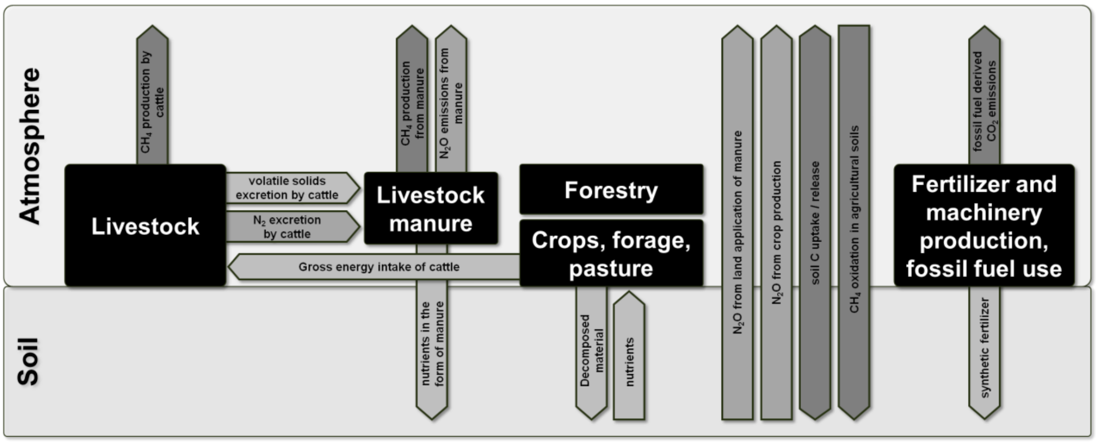


Figure 1. Sources of greenhouse gas emissions and carbon fluxes from agriculture and forestry. Adapted from Stewart et al. (2009).

The anthropogenic sources of GHGs described above are additional to the expected sources of gases as part of their normal cycle in a natural environment (Figure 2). Actions aimed at increasing the productivity of food production have altered the natural equilibrium of these cycles, increasing emissions of GHG to the atmosphere (IPCC, 2007a). Although CH_4 from cattle is the largest contributor, this is an unavoidable outcome of rumination. On the other hand, grasslands and forests constitute one of the main sources of C sequestration by agricultural systems, as a result of their photosynthetic activity (Soussana et al., 2007). Therefore, understanding how these gases are added to and removed from the atmosphere is germane in order to study their abatement at a farm and national scale.

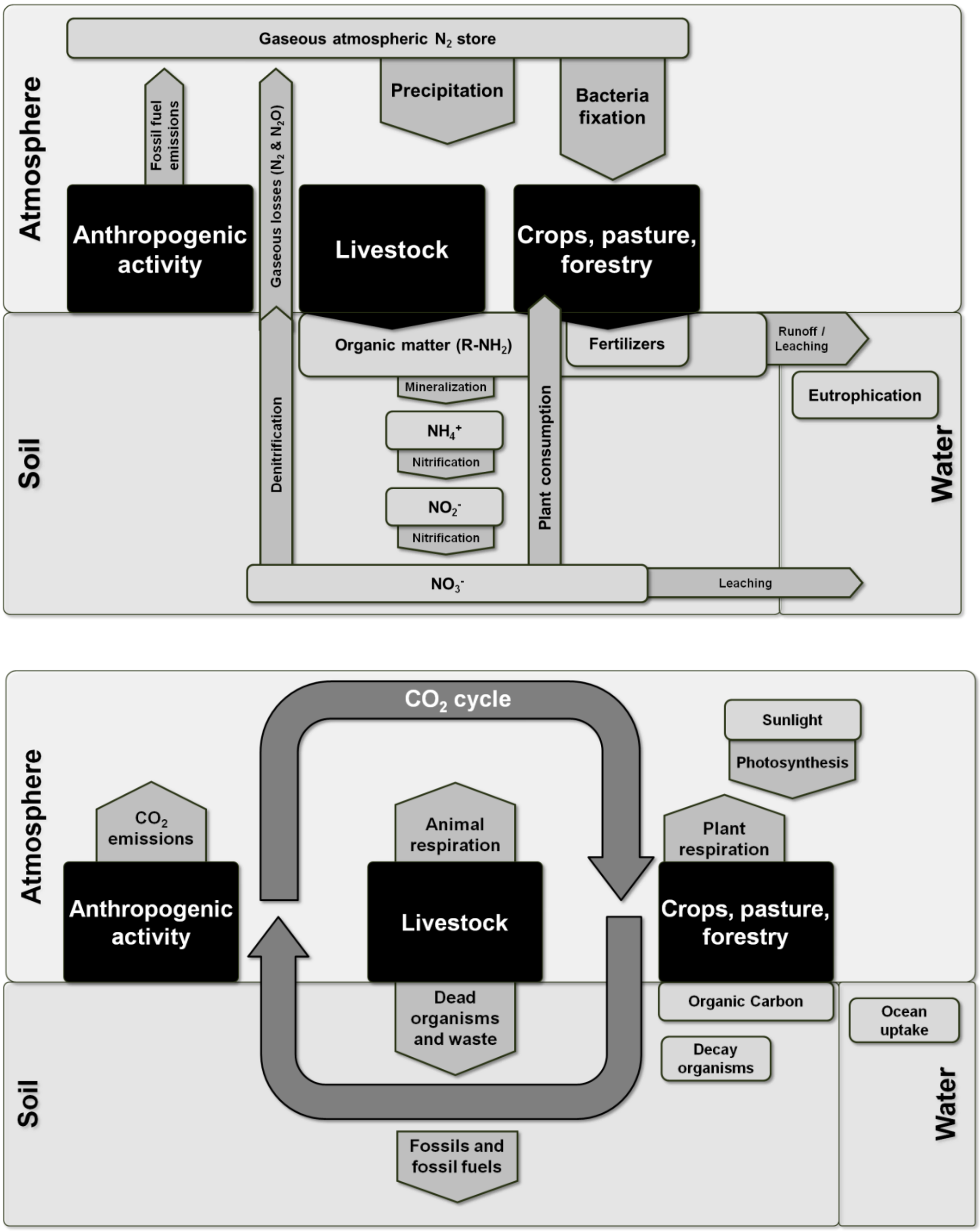


Figure 2. Nitrogen and carbon cycles in natural ecosystems

1.2.1 Emissions from crops and soils

Activities related to soil management and crop production contribute to emissions of CO_2, CH_4 and N_2O (Figure 2). Globally, CO_2 emitted from soil respiration has been reported to be 10 to 15 times greater than emissions from fossil fuel (Raich and Schlesinger, 1992). However, these sources of CO_2 emissions are not accounted in the current methodology for GHG inventory suggested by IPCC (2006). From all emissions to the atmosphere, a third of CH_4 and two-thirds of N_2O are emitted from soils (Prather et al., 1995). Sources of soil C loss include microbial and plant respiration, hence any factor which could change the size of these fluxes will affect the amount of CO_2 emitted (Smith et al., 2003; Rees et al., 2005). Although animal rumination is the main contributor of agricultural CH_4 emissions, a lower amount of this gas is emitted from the soil through decomposition of organic compounds by strictly anaerobic microorganisms (MacDonald et al., 1998; Smith et al., 2003). In some cases, CH_4 can also be oxidized to CO_2 by aerobic bacteria contributing to the pool of CO_2 emissions (Brumme and Borken, 1999). Nitrous oxide from soils can be emitted directly or indirectly. Direct emissions refer to N_2O produced via nitrification and denitrification of N in the soil (in their diverse forms). Indirect emissions represent the N loss through the volatilization of ammonia and nitrogen oxides, or the leaching and runoff of nitrates (IPCC, 2006). Globally soils contribute large amounts of N_2O emissions (9.5 Mt $N_2O\text{-}N \cdot year^{-1}$) representing 65% of the total N_2O-N global emissions, of which 37% are produced from agricultural soils and 11% in temperate grasslands (Flechard et al., 2007). The main sources of N_2O emission from the soil are direct emissions from microbial nitrification and denitrification processes (Beauchamp, 1997). Because the denitrification process needs anaerobic conditions, the level of the water table, temperature and structure of the soil are important in determining rates of N_2O emissions (Smith et al., 2003).

On the other hand, soils and grasslands are important locations of CO_2 sequestration. Carbon is sequestered in agricultural soils, grasslands and woodlands (Johnson et al., 2007). In grazed grasslands, plants fix C through their photosynthetic activity. This C is used within the plant for energy supply or structural growth. Moreover, root turnover, senescent tissue and litter deposition are directly deposited in the soil contributing to its C storage. Under grazing conditions, although grass material is removed by grazers, the non-digestible proportion of the forage for the animals is then returned to the soil through direct dung deposition or later by manure application (Soussana et al., 2004). Carbon can also be sequestered by oxidation of atmospheric CH_4 to CO_2 by methanotrophs in the soil (Dijkstra et al., 2013). Different ecosystems have their particular C storage potential due to the main characteristics of the environment allowing balances between C storage and C respiration or forage utilization (Soussana et al., 2004). For instance, hill soils in Scotland are very carbon rich. Northern peatlands are significant sources of C storage, as they contain between 20 to 30% of the global terrestrial carbon stocks in only 3% of the land area (Worrall and Evans, 2009). Peatlands in the UK represent 12% of the land area, and distinct from other peatlands in the northern hemisphere in the UK they are extensively managed (Worrall and Evans, 2009). However measuring changes in C stocks is a very difficult task and as far as it has been reported, large changes in C storage are probably not happening at the moment (Buckingham et al., 2013). Thus, considering the issue of C sequestration into the C budgeting of agricultural systems carries inherent uncertainty.

There are considerable land use issues related to beef production, contributing different C footprints. Different amounts and types of grasslands are used in different systems, with various soil types, a range of N_2O output profiles and varied C sequestration potential (Soussana et al., 2007). Moreover, processes of growing grass for grazing, producing forage for housed feeding, growing cereal and concentrated feed either on or off the farm have different GHG profiles. Some of these activities have profound effects on N_2O output due to their dependence on fertiliser and/or manure inputs. All of these practices interact with farming method and have diverse direct outputs of GHG from the land, linked to the livestock system. These interactions are not well understood, and may be influenced by particular decision making of individual farmers. Many management options have been reported to reduce the level of emissions from these sources and they will be explained in more detail below. Thus, it is important to understand how emissions from land use and ruminants occur and how they can be reduced in order to investigate interactions at the system level.

1.2.2 Emissions from ruminants

One of the main characteristics of ruminants is their ability to degrade fibrous carbohydrate feeds due to their symbiotic relationship with microorganisms in their rumen. Various bacteria species are able to degrade a range of carbohydrates through anaerobic fermentation. The main end-products of their fermentation are volatile fatty acids (VFA), CO_2, hydrogen (H_2), ammonia and heat. The principal VFAs produced by fermentation are acetate, propionate and butyrate, which are used by the animal as a source of energy and precursors for synthetic processes (Tamminga et al., 2007). The H_2 is also used to hydrogenate unsaturated lipids present in the feed and also production of ammonia in the N cycle (Bannink and Tamminga, 2005; Waghorn et al., 2006). Remaining H_2 is used by methanogenic *Achaea* spp. to generate CH_4 by reducing CO_2. The CH_4 produced is not usable by the animal and is released. Most of the CH_4 (85-90%) is produced in reticulo-rumen fermentation and released as gas by eructation, while soluble CH_4 generated by ruminal and intestinal fermentation is absorbed into the blood and released through respiration. A small percentage of the gaseous CH_4 (< 2%) is lost throughout the flatus (Murray et al., 1976). Methane is also produced from faeces and manure once this is either directly deposited in the field by grazing animals or managed for further application to agricultural soils (Steed and Hashimoto, 1994).

Nitrous oxide is also indirectly emitted by ruminants from their excreta as part of the N cycle (Figure 3). The protein content of the feeds is hydrolysed to peptides and amino acids by the microorganisms in the rumen and some amino acids are further degraded to organic acids, ammonia (NH_3) and CO_2. These compounds are used by the microorganisms to synthesise their own proteins, being the major source of protein for the animal. When the degradation of proteins is higher than the synthesis capacity, ammonia is accumulated in the rumen. This is then absorbed through the rumen wall to the blood and carried to the liver where it is converted into urea. Part of this urea is recycled and returned to the rumen via saliva, but a larger proportion is excreted in the urine (McDonald et al., 1988). Urine patches from grazing animals are major contributors to N_2O emissions. Animals excrete N as urea and once in the soil it is transformed to nitrogen gases such as ionised ammonia (NH_4), which is highly volatile; this NH_4 is transformed into nitrates (NO_3) through nitrification and a proportion of this is afterwards transformed into N_2O by denitrification processes (Di et al., 2007; Di et al., 2010).

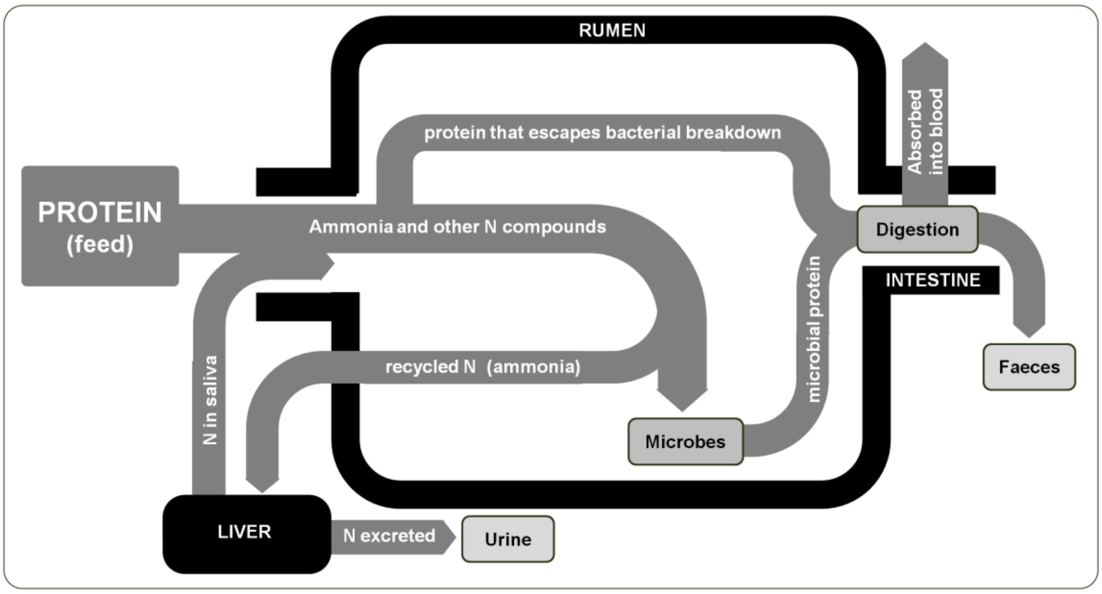


Figure 3. Nitrogen cycle in ruminants.

In addition to the emission of N_2O from grazing animals, N_2O is also directly and indirectly emitted during manure storage and indirectly when applied to the soil. Direct emissions are those generated by the nitrification (oxidation of ammonia to nitrate) and denitrification of the N contained in manure. Nitrification occurs during the storage of manure and presence of oxygen is required for the process (more significant process in solid-dry manure storage). Denitrification is an anaerobic process (predominant during liquid manure storage) where nitrites and nitrates are transformed to N_2O and di-nitrogen (N_2). In this way, a stage of aerobic nitrification where nitrates are produced is followed by an anaerobic denitrification to produce N_2O. Indirect emissions of N_2O from manure are a consequence of volatilization, leaching and run-off when manure is applied to soils constituting a major water pollutant causing eutrophication and soil acidity (U.S.EPA, 2006; DEFRA, 2010).

1.3 Scope for mitigation

Several management alternatives have been reported to reduce GHG emission rates from land and livestock management and the most relevant strategies mentioned in the literature are described below.

1.3.1 Land use management

The use of inorganic fertiliser is one of the most important sources of GHG emissions. A considerable amount of energy is used in their manufacture and carries with it called embedded CO_2 emissions. The estimated annual N_2O emissions from fertiliser application are variable depending on soil type and weather. For example, annual emissions of 0.5 and 3.9 kg N_2O–N ha^{-1} yr^{-1} resulted from an application of 100 kg N in the East and the West of the UK, respectively (Cardenas et al., 2010). Fertiliser or manure application management can also have an impact on the total emissions of the system. Practices like reducing either by half or eliminating the use of fertiliser resulted in large reductions in N_2O emissions (Nyborg et al., 1997; Stewart et al., 2009). However, this practice increased emissions per unit of protein produced, due to the reduced productivity of the system (Stewart et al., 2009). The use of fertiliser also has an impact on the protein content of temperate (Reeves et al., 1996) and tropical (Davison et al., 1985) forage species. Different levels of fertiliser application can therefore have an impact on pasture quality with a consequent influence on emissions from animal enteric fermentation and manure (CH_4 and N_2O). Other studies suggest that the addition of nitrogen to the soil impedes the organic matter decomposition and stimulates C sequestration, which finally results in a substantial reduction of the net CO_2 emissions (Janssens et al., 2010), but this effect is small relative to the high N_2O emissions created (Johnson et al., 2007). More information is needed to fully understand the interaction between C and N and their effect on N_2O emissions. The latter is only one example where managing grasslands with the aim of increasing their C sequestration potential may have as a trade-off an increase in CH_4 and N_2O emissions and a reduction in the productivity of the system (Soussana et al., 2004). Therefore, a more systemic analysis is essential to evaluate the relative contribution of each practice on the resulting net C footprint of beef farms.

The use of legume species has been proposed as an alternative to reduce N_2O emissions as they can fix N from the environment to the soil as a result of their symbiotic relationship with microorganisms (Yan et al., 2013). Therefore, use of grass and legumes in mixed pastures has been claimed to reduce total C equivalent emissions at the system level as a result of the lower need for N fertiliser and by providing cattle with a forage with higher energy and protein content for their diets (Frame and Laidlaw, 2011). However, efficient use of high levels of protein supplied by legumes can only be achieved by synchronising the available energy and protein for ruminal fermentation (Evans et al., 1996) as an excess of N supply can cause an exponential increase in N excretion (Castillo et al., 2001).

Studies have also shown the potential application of nitrification inhibitors to the soil in order to reduce losses of N_2O from urine patches in grazed fields. These studies have proved the significant effectiveness of the inhibitor dicyandiamide even in different types of soils. Reductions from 61 to 70% of the nitrification process can be expected from its application to a range of soil types (Di et al., 2007; Di et al., 2010). Most recently, however, use in New Zealand has ceased due to concerns over contamination of milk.

In terms of land use management, it has been mentioned that either increasing organic matter inputs to the soils, decreasing the decomposition of soil organic matter (SOM) and soil organic carbon (SOC) oxidation or a combination of these are used as methods to increase CO_2 sequestration from the atmosphere and convert it into SOC (Paustian et al., 2000; Follett, 2001). Therefore, practices such as reducing tillage intensity have been found to be positively related with C sequestration (West and Post, 2002). However, it is important to consider possible increments on N_2O emissions with no-tillage systems due to soil compaction, reduced porosity and increased denitrification (Smith and Conen, 2004). Decreasing or ceasing the fallow period, using winter cover crops, changing from monoculture to rotation cropping, and altering soil inputs to increase primary production (i.e. fertilizers, pesticides, irrigation) are some alternatives proposed to mitigate emissions from the soil-crop sub-system. However, it is important to analyse them with a systemic approach as their application could have an impact on other parts of the system (Stewart et al., 2009).

Adding forestry to agricultural land (i.e. agroforestry) is one way to increase even further the amount of C sequestered per unit of land, with complementary advantages such as avoidance of soil and nutrient loss, diversification opportunities for the system, improvements in animal welfare, preservation of wildlife habitats and biodiversity conservation (Rigueiro-Rodriguez et al., 2008). Agroforestry can also help to reduce CH_4 and N_2O emissions by regulating the level of the water table (Worrall and Evans, 2009). The presence of forest may also affect the amount of C stored in the soil. As the forest grows, it makes use of the available C to generate its own biomass by increasing SOC decomposition (Cannell et al., 1993).

1.3.2 Animal and herd management

Many strategies to reduce methane emissions from farmed ruminants grazing on pasture have been mentioned in the literature and extensively reviewed (Kreuzer and Hindrichsen, 2006; Waghorn and Clark, 2006; Iqbal et al., 2008; Reynolds et al., 2010; Eckard et al., 2010; Martin et al., 2010; Shibata and Terada, 2010; Buddle et al., 2011).

The type of feed, its nutritive characteristics and level of intake are the main factors which determine, in a complex way, the amount of CH_4 produced by the animal (Johnson and Johnson, 1995). These characteristics influence the level of fermentative activity, the type of microorganisms growing in the rumen and the degradation dynamic of the ruminal content (Okine et al., 1989; Ominski et al., 2006; Hammond et al., 2009). The amount of CH_4 produced is related to the type of fermentation that takes place in the rumen. High fibre-content diets will produce a higher acetate:propionate ratio which is associated with more H_2 production, whereas a greater proportion of propionate will provide a source to sink H_2 (Tamminga et al., 2007). Therefore, the larger the proportion of forage in the diet, the greater the amount of CH_4 produced from the system per unit of feed consumed. Coarse feeds stay longer in the rumen and may also contribute to CH_4 production. For that reason, many authors maintain that the higher the fibre content of the feed, the higher the expected CH_4 production (Bannink et al., 2010).

The proportion of consumed energy lost as CH_4 ranges from 2 to 12% of the gross energy intake (GEI), depending on the quality of the diet (Johnson and Johnson, 1995). A number of dietary management alternatives can affect the amount of CH_4 production to manipulate ruminal micro-flora (Johnson et al., 1994; Beauchemin et al., 2008; Buddle et al., 2011). Some of the extensively reviewed options to reduce enteric CH_4 emissions are the type of carbohydrate included in the diet (Mills et al., 2003; Beauchemin and McGinn, 2005), use of high energy feeds (Frame and Laidlaw, 2005; Jentsch et al., 2007; Stewart et al., 2009; Yan et al., 2009; Yan et al., 2010), proportion of forage in the diet (Moe and Tyrrell, 1979b; Holter and Young, 1992; Blummel et al., 2005; Ellis et al., 2007; Yan et al., 2009; Yan et al., 2010), use of legumes species (Varga et al., 1990; McCaughey et al., 1999; Boadi and Wittenberg, 2002; Frame and Laidlaw, 2005; Stewart et al., 2009), modification of the physical form of grains (Moe et al., 1973a; Moe and Tyrrell, 1977) or hay (Hironaka et al., 1996), use of lipids (Machmüller et al., 1998; Boadi et al., 2004; Beauchemin and McGinn, 2006b; Jentsch et al., 2007; Beauchemin et al., 2007; Grainger et al., 2008b; Benchaar and Greathead, 2011; Grainger and Beauchemin, 2011) or other dietary additives such as ionophores (McCaughey et al., 1997; Sauer et al., 1998; Beauchemin et al., 2008; Grainger et al., 2010b), condensed tannins (Puchala et al., 2005; Waghorn, 2008; Grainger et al., 2009; Hassanat and Benchaar, 2013), saponins (Holtshausen et al., 2009), malic acid (Foley et al., 2009), fumaric acid (McGinn et al., 2004), yeasts (McGinn et al., 2004; Muñoz et al., 2012), enzymes (McGinn et al., 2004; Shinkai et al., 2012) or even the use of different plant species like *Rheum nobile*, *Carduus pycnocephalus* and *Populus tremula* for their anti-methanogenic effects demonstrated *in vitro* (Bodas et al., 2008), or through manipulation of the rumen such as vaccination or defaunation (Hook et al., 2010).

Although some of these strategies have been found to reduce emissions at the animal level, there is a need to study their potential mitigation effect at the farm system level. The use of additives or supplements was shown to reduce the time to slaughter reducing the total carbon footprint of the system (Jordan et al., 2006). However, it has also been argued that in grazing animals the use of supplements is of secondary importance, as the quality of the pasture is the determinant of CH_4 emissions. For example, CH_4 yields were 44% and 29% lower from steers grazing an early stage pasture compared with mid and late stage, whilst the use of barley grain did not reduce CH_4 outputs (Boadi et al., 2002b). However, CH_4 yields from beef heifers was not affected by different digestibility of a ryegrass pasture (Hart et al., 2009). Thus, the long-term impacts and possible interactions of the application of these mitigation options also need further attention.

It is also important to consider the N cycle of the animals, as they indirectly contribute to N_2O emissions by their urination in grazed pastures and from their manure (Kebreab et al., 2006). From a nutritional point of view the more balanced the diet in terms of energy and protein supply, the more efficient the utilization of the feed by ruminal microbes (McDonald et al., 1988; Varga et al., 1990). Consequently it is important to consider these possible losses of N from the animal, mainly when other management practices oriented to reduce CH_4 emissions from rumination are applied (Ellis et al., 2012). Most of them tend to increase the quality of the diet, thus it is relevant to take into account the balance of the protein or N content of the diets and consider possible trade-offs while trying to reduce CH_4 and N_2O emissions.

The efficiency of use of energy and animal performance has been mentioned to have a significant relationship with CH_4 emissions in dairy cows (Yan et al., 2010). There is clear evidence that CH_4 yield declines when increasing the feeding level above maintenance (Sauvant and Giger-Reverdin, 2009; Muetzel et al., 2009; Yan et al., 2010). Using a simulation model it was mentioned that a reduction of 15% of CH_4 emissions per ha is possible to be achieved by increasing the feed conversion efficiency (Beukes et al., 2010). Although monitoring the residual feed intake (RFI) of animals (as the difference between actual and predicted intakes) was found to explain only a small variation of their CH_4 emissions (Hegarty et al., 2007), this index has been described as an indicator of animal efficiency with the potential to be applied in breeding selection programs (Waghorn and Hegarty, 2011; Roehe et al., 2012). It has been reported that dairy cow genotypes selected for high genetic merit for milk yield also had lower CH_4 emissions (Münger and Kreuzer, 2006; Chagunda et al., 2009a). Still, the productive lifetime of high genetic cows selected for production traits is often shorter (Münger and Kreuzer, 2006) and feed required is higher in intensively managed systems (Chagunda et al., 2009a), hence this factor requires further study at the system level.

Maximizing feed intake reduced the consumed energy lost as CH_4 (Johnson and Johnson, 1995; Hironaka et al., 1996; Beauchemin and McGinn, 2006a). At the system level, this indicates that feeding cattle for maximum performance is important to reduce CH_4 emissions as it reduces the proportion of energy lost as CH_4 each day and the number of days the animals need to be finished (Hyslop, 2003; Beauchemin and McGinn, 2006a; Stewart et al., 2009). Seasonal variation in CH_4 emission from herds (Ulyatt et al., 2002) and flocks (Ulyatt et al., 2002; Muetzel et al., 2009) has been reported, mainly as a response to the physiological stage of the animal. However, this has not been addressed yet in beef farming systems. This can help to reduce the uncertainty of GHG predictions with accurate estimates of their emissions throughout the year.

The importance of a systemic analysis of GHG at farm level is associated with understanding what happens in the whole system when changes of management are applied to any of its parts. For instance in dairy farms, keeping more efficient cows under extensive management, elimination of non-milking animals and a combination of both scenarios were able to reduce the CO_2 equivalent emissions per kg product per year by 28-33% (Casey and Holden, 2005). In addition, improvements in herd reproductive efficiency resulted in a 5% reduction in CH_4 whilst a 15% reduction in CH_4 emissions per ha is achievable by increasing animals feed conversion efficiency, primarily by reducing the dry matter intake (DMI) and maintaining the same performance levels (Beukes et al., 2010).

Altogether, it is evident that more studies with a holistic point of view are needed considering consequences in other components of the system, such as emissions from feed production and manure. As previously mentioned, grasslands are an important source of food for ruminants, therefore more studies focused on grazing management, GHG emissions and biodiversity conservation are essential.

1.4 Beef production systems in UK/Scotland

Studies have been carried out considering mitigation options on beef production at the system level (Stewart et al., 2009; Foley et al., 2011), an examples if inputs and outputs of such models are shown in Table 1.

Table 1. Inputs and outputs considered for predicting greenhouse gas emissions in agricultural system models

Inputs	GHG outputs
Number of animals and physiological stage	Enteric CH_4
Feed quality (Digestibility, Gross energy)	
Animal performance and intake	
Number of grazing and indoor animals	Manure CH_4 and N_2O
Stored manure management	Manure indirect N_2O
Intake, digestibility, nitrogen excretion	
Type of crop and crop residues	Soil CH_4 and N_2O
Number and type of soil labours	
Organic and inorganic fertiliser	
Fuel and electricity use	Energy use CO_2
External inputs (e.g. fertilisers, supplements)	Embedded CO_2

A holistic approach is urgently needed in order to understand interactions between alternative management. Moreover, it is important to study the range of possible applications and final mitigation potential of the application of a series of mitigation options at the system level, due to the large variety of farm typologies. There is still a gap in the knowledge on the overall interactions and mitigation potential at national and global scale of diverse management alternatives to reduce carbon footprints of livestock production. For instance, 61% of the agricultural area in the UK is occupied by permanent grassland and common rough grazing, 6% by woodlands and 33% is arable land. Furthermore, 20% of this arable area is temporary grassland (National Statistics, 2009). In Scotland, 58% of the total agricultural area is rough grazing land and 70% of the arable land is pastures (Scottish Government, 2009). Thus, diverse management options would have different levels of adoption and relatively different impacts on GHG emissions depending on the characteristics of the farming systems. The global challenge for the agricultural sector is reducing GHGs and increasing food production. With such diverse farming conditions it is relevant to further investigate the possibilities (increasing efficiency of the production system) and limitations (shortage of land available, less favoured areas, low incomes) of achieving this objective at a larger scale.

Different types of farms can be differentiated within the UK according to their location and environmental characteristics, driven by weather conditions, soil and grassland quality. Those farms located in higher altitudes generally have less than 10% of their area suitable for fodder production, while the remaining 90% is low quality grassland. Farms located in the hill areas have limited possibilities of improvement in outputs of land and animals when compared with others in the lowlands. The weather is harsher and the quality of their soils is poor, which prevents the sowing of improved pastures or crops to produce cereals. However, hill grasslands constitute an important source of feed for grazing ruminants. The hill vegetation is characterised by a cold and wet climate, with a consequent short grass growing season. The most common vegetation types in the hill are *Calluna vulgaris* (dwarf shrub based on acid and often peaty soils in high altitudes), *Nardus stricta* (tussock forming plants on less acid and dry soils), *Molinia caerulea* (broad-leaved deciduous plant growing on wet but not waterlogged soils) and *Agrostis* spp. and *Festuca* spp. communities predominating in more rich-soils (Armstrong et al., 1997b). Farms in uplands are located at an intermediate altitude. Up to 40% of their area is good quality (inbye) which can be designated for cereals and winter forage making, while the remaining area consists of low quality grassland used for continuous grazing. At lower altitudes, the soil and climate characteristics allow a wider variety of land uses compared with highlands. Sown or established pastures for grazing, silage or hay production may compete with crop production for cereals or animal supplements, predominately by barley and wheat. These farms have more possibilities for intensification and diversification where more than 40% of their land can be used to produce winter forage for cattle, compared with those in the hills or uplands (Armstrong et al., 1997b).

This range of different farming conditions leads to a large uncertainty when trying to predict GHG emissions at the farm, or even regional or national scale. These uncertainties are driven by the lack of ability to quantify GHGs from extensive systems by available methodologies under more realistic and practical conditions, therefore leading to uncertainties in gas emission factors for grazing-based systems. In these types of systems such as those in the hill and upland regions of Scotland or the large native grasslands and rangelands in the plains and mountains of Argentina, cattle are commonly gathered once or twice a year. There are large uncertainties in the C footprints of these systems and numerous assumptions are made upon the grazing behaviour, grazing choice and intake levels (as examples) of cattle managed extensively. There is still a lack of information on how important these uncertainties might be and how this issue can be represented in final estimates of the environmental impact of ruminant-based systems. Consequently, it is relevant to review the literature regarding GHG quantification and prediction approaches to further understand how these distinguishing issues of grassland based systems can be addressed in future research work.

1.5 Measuring methane emissions

Several methods are available to measure enteric CH_4 outputs (Bhatta and Enishi, 2007; Storm et al., 2012). Calorimetric chambers have been used for full accounting of energy used by animals. This method allows measurements of the gas emitted by the animal as the difference between inlet and outlet air-flows, and in most cases faecal and urine excretions are also quantified. This first method to quantify CH_4 outputs has been broadly used for a variety of studies (Moe and Tyrrell, 1979b;

Cammell et al., 1986; Varga et al., 1990; Moss et al., 1994; Kirkpatrick et al., 1997; Lachica et al., 1997a; Lachica et al., 1997b; Murray et al., 1999; Estermann et al., 2002; Moss and Givens, 2002; Boadi et al., 2004; McGinn et al., 2004; Wright et al., 2004; Beauchemin and McGinn, 2005; Blummel et al., 2005; Hindrichsen et al., 2005; McGinn et al., 2006; Münger and Kreuzer, 2006; Beauchemin and McGinn, 2006a; Beauchemin and McGinn, 2006b; van Dorland et al., 2007; Grainger et al., 2007; Pinares-Patiño et al., 2008a; Grainger et al., 2008a; Piatkowski et al., 2010; Yan et al., 2010; Grainger et al., 2010b; Goopy et al., 2011; Pinares-Patiño et al., 2011a; Pinares-Patiño et al., 2011b; Shinkai et al., 2012; Garnsworthy et al., 2012; Muñoz et al., 2012; Jiao et al., 2013).

A variety of methods have been developed to measure CH_4 from sampled air of individual animals without the need to introduce them to a chamber. For example, mask calorimetry (Belyea et al., 1985), hood calorimetry (Okine et al., 1989; Nkrumah et al., 2006; Ellis et al., 2009), gas sampling during milking (Garnsworthy et al., 2012) or a plastic tank connected to a small ruminal fistula (Berra et al., 2009). These methods have been applied to indoor or enclosed feeding conditions.

Other methodologies have been developed to measure CH_4 outputs from grazing animals. Probably the first technique designed with this aim was the 'SF_6 tracer technique'. This method is based on the use of a controlled released bolus of the inherent sulphur hexafluoride (SF_6) gas inside the rumen of the animal. By collecting sampled air in an evacuated canister carried on the neck or the back of the animal, the amount of CH_4 can be estimated as a ratio of the collected volume of the tracer gas of which the emission rate is previously known (Johnson et al., 1994). This technique has been widely adopted (Lassey et al., 1997; McCaughey et al., 1997; McCaughey et al., 1999; Leuning et al., 1999; Boadi and Wittenberg, 2002; Boadi et al., 2002a; Boadi et al., 2002b; Boadi et al., 2004; Wright et al., 2004; Vlaming et al., 2005; McGinn et al., 2006; Ominski et al., 2006; Chaves et al., 2006; Machmüller and Clark, 2006; Guan et al., 2006; Sneath et al., 2006; Grainger et al., 2007; Pinares-Patiño et al., 2007; Allard et al., 2007; Hegarty et al., 2007; Soussana et al., 2007; Vlaming et al., 2007; Cavanagh et al., 2008; Vlaming et al., 2008; Pinares-Patiño et al., 2008a; Pinares-Patiño et al., 2008b; Grainger et al., 2009; Foley et al., 2009; Hammond et al., 2009; Holtshausen et al., 2009; Ramírez-Restrepo et al., 2010; Ding et al., 2010; Wims et al., 2010; Grainger et al., 2010a; Grainger et al., 2010b; O'Neill et al., 2011; Lassey et al., 2011; Pinares-Patiño et al., 2011a; O'Neill et al., 2012; Muñoz et al., 2012; Pedreira et al., 2012).

Nevertheless, the success of this method is variable. For instance, some authors reported good agreement when comparing the SF_6 technique against respiration chambers (Boadi et al., 2002a), while others did not find significant correlation between methods (Wright et al., 2004). Furthermore, over- (Wright et al., 2004; Pinares-Patiño et al., 2007) and under-estimation (McGinn et al., 2006; Grainger et al., 2007) of chamber based measured CH_4 have been reported in the literature. Animal-to-animal variation was observed to be higher when using the SF_6 technique than with respiration chambers, which implies that greater numbers of animals are needed for measurement with the tracer method to determine treatment differences (Lassey et al., 1997; Boadi et al., 2002a; Grainger et al., 2007). Furthermore, a negative effect on DMI can be expected in animals wearing the harnesses of SF_6 equipment (Hegarty et al., 2007). The application of this method to a large number of animals is quite laborious and time-consuming. This technique is not feasible for use in extensive systems, such as hill grazing or large rangelands, as it requires gathering animals once a day to change the gas-collecting canisters.

Another method proposed to quantify CH_4 from grazing animals is the use of a polyethylene tunnel (Lockyer and Jarvis, 1995). This method, which in principle works similar to a respiration chamber, has allowed observations of diurnal grazing patterns of animals in the tunnel with fluctuating CH_4 production as a result of their grazing behaviour (Lockyer and Champion, 2001; Dengel et al., 2011).

Mass-balance (Denmead et al., 1998), micro-meteorological techniques (Sauer et al., 1998; Judd et al., 1999; Laubach and Kelliher, 2004) or open-path eddy covariance (Dengel et al., 2011) have been used to sample CH_4 at different levels in the atmosphere in paddock scale applications. Similarly, using an open-path laser technique, CH_4 outputs from grazing animals can be assessed from a paddock (Laubach and Kelliher, 2005). These techniques have been mentioned to be good at quantifying net gas emissions at the paddock scale and of a static place. However, their application for comparisons between individual animals, breeds, types of grassland or even extensive management conditions is still limited.

The Laser Methane Detector (LMD; Tokyo Gas Engineering Co. LTD) developed as a monitoring devise to assess CH_4 leaking pipes or emissions from landfills among others, is a promising methodology for measuring CH_4 from ruminants on their natural environment, as shown when applied to dairy cows indoors (Chagunda et al., 2009b; Chagunda and Yan, 2011). Measurements collected with the LMD have been compared with air collected from chambers, showing good agreements (Chagunda and Yan, 2011). Some advantages of this methodology mentioned in that work involve its ability to operate normally in a wide range of temperatures and humidity conditions. Also, it can record measurements at a distance without disturbing animal activities and eating behaviour. However, its application on grazing animals has not been reported yet. Other benefits are that it is a non-invasive technique. Thus, animals do not need to carry any equipment, avoiding any potential disturbance to diet selection or the level of DMI. In addition, results obtained with LMD were positively related with DMI (Chagunda et al., 2009b). However, an independent validation of this method has not yet been conducted for testing its ability to differentiate between CH_4 mitigation alternatives. Further studies are needed for a better understanding of which factors may introduce variability to the LMD-measures before further assessment of grazing animals under different management situations.

As shown, there are a variety of methods to measure CH_4 emissions. Although respirometers are accurate and precise for measuring all the CH_4 emitted from an animal, in many cases they fail to represent animals' natural conditions, particularly for animals under extensive management (Osuji, 1974) whose diets are highly determined by diurnal grazing behaviour and selection of species in grasslands and where their daily manipulation does not reflect their natural behaviour.

1.6 Predicting greenhouse gas emissions

Estimates of C emissions have been used not only at the animal level but also at farm, national and global scale. Diverse modelling approaches are mentioned in the literature from simple static empirical to more complex dynamic mechanistic models.

Often, mechanistic models are a compound of linear, non-linear, simple or multiple regression equations. However, optimization models based upon linear (or non-linear) programming constitute another example of mathematical approaches applied to animal science. This last approach is commonly used for finding the optimum answer to a given problem by changing dependent variables subjected to given constrains. This approach is commonly used for least-cost ration prediction, where the optimum response will be to achieve the desired performance level with the condition that this involve the minimum costs (France and Kebreab, 2008).

Empirical models are derived from curve-fitting experimental observations and their application is limited to the range of situations from which they were developed. Mechanistic modelling is applied to understand mechanisms that explain a response, often used in system analysis considering interactions between system components or sub-systems (France and Kebreab, 2008). For instance, empirical models have been developed to predict CH_4 emissions from ruminants while considering different aspects of the animal and/or diet characteristics (Kriss, 1930; Bratzler and Forbes, 1940; Blaxter and Clapperton, 1965; Moe and Tyrrell, 1979b; Holter and Young, 1992; Yan et al., 2000; Mills et al., 2003; Machmüller and Clark, 2006; Ellis et al., 2007; Yan and Mayne, 2007; Ellis et al., 2009; Yan et al., 2009; Piatkowski et al., 2010).

Models for predicting energy and protein requirements of ruminants (e.g. AFRC, 1993; NRC, 1996) are examples of mechanistic models constructed from empirical relationships. These models are then integrated to decision-making models applied for example to the nutritional management of livestock systems (e.g. Cornell Net Carbohydrate and Protein System is the most widely known practical model for dairy cattle nutrition (McNamara, 2004)), the environmental impact and economics of dairy (Benchaar et al., 1998; Lovett et al., 2006; Schils et al., 2007a; Beukes et al.,

2008) and beef systems (Rotz et al., 2005; Stewart et al., 2009; Veysset et al., 2010; Foley et al., 2011; Sise et al., 2011), for simulating pasture growth (McCall and Bishop-Hurley, 2003; Barrett et al., 2005), integrating responses of grassland utilization (Armstrong et al., 1997b), land-use practices in pasture systems (Ford-Robertson et al., 1999), arable farms (Lindgren and Elmquist, 2005) or for predicting N_2O emissions from grazed grasslands (Saggar et al., 2007). Mechanistic models based on empirical assumptions have even been applied to foot-printing the total GHG emission from agriculture (RBU, 2011) at the farm level; also to describe the total emissions throughout a product chain such as Life Cycle Assessments (Weiss and Leip, 2012), and more generally to account for the environmental footprint of diverse economic sectors up to the national and global scale (IPCC, 2006).

Models to predict CH_4 have previously been evaluated against observed data (Kebreab et al., 2008). Ellis et al. (2010) mentioned that more sophisticated prediction equations estimate observed CH_4 values more accurately than those based upon simple empirical relationships. Previous studies have demonstrated that mechanistic models at the level of rumen metabolism for predicting CH_4 (e.g. Baldwin, 1995) explained better the variation observed in measured CH_4 emissions than empiric equations (Benchaar et al., 1998). However, the application of a given model strictly depends on the data availability to perform simulations and its application to the practical level is often limited by the information required (Tedeschi et al., 2005; France and Kebreab, 2008). In these cases mechanistic models based upon simple empirical relationships between performance data and dietary characteristics (e.g. AFRC, 1993) are useful to interpret potential impacts of observed responses in experimental studies and scale them up to the whole-farm level.

The level of complexity of the model will determine its ability to analyse effects of new factors, new measurements or interactions between variables already included in the model (Tamminga et al., 2007). As part of my literature review I performed a Monte Carlo simulation to study the impact of using a different CH_4 prediction equation upon the system results when diverse management conditions are compared, such as hill vs. lowland type of grassland (Ricci and Waterhouse, 2011).

Although I do not include these results in my thesis, this study demonstrated that the use of different equations has a significant impact at the system level, highlighting the need for further studies to understand factors affecting CH_4 prediction not only at the whole-farm, but national scale where management alternatives are so diverse.

Although attempts have been made to predict CH_4 from different types of diets (Blaxter and Clapperton, 1965; Jentsch et al., 2007); these represent only the spectrum of indoor fed animals. There is only one CH_4 prediction equation in the literature that has been developed specifically from grazing animals (Machmüller and Clark, 2006), while there are more than 80 published equations for indoors animals. Further, there is a lack of studies that investigate nutrient budgets from extensive semi-natural grasslands, reflecting the lack of understanding of their contribution to the global issue of carbon emissions. Their characteristic spatial and temporal heterogeneity, diversity of plant species and plant communities, their interactions, nutritional value for ruminants and their response to utilization by grazing animals are some of the features that describe the complexity of grassland environments.

Large uncertainties in CH_4 and N_2O predictions (IPCC, 2006) are a consequence of large temporal and spatial variability and limitations in measurement technologies (Flechard et al., 2007), lack of understanding of biological systems, poor validation of results and weather-induced variability (Gibbons et al., 2006). Uncertainties on emission factors have been considered in some studies when concluding about the effect of management alternatives on mitigating GHG emissions of whole-farm systems, reflecting the cumulative probability to obtain a result rather than a single point answer (Lovett et al., 2008; Foley et al., 2011). Uncertainties over CH_4 prediction from enteric fermentation and manure management of 22 and 52% respectively, were mentioned when scaling up predictions based on IPCC (2006) for a national scale budget, reflecting the need for more specific emission factors for more accurate estimates of C footprints (Karimi-Zindashty et al., 2012).

Reducing the uncertainty over GHG budgets and reflecting the large variation in response of the intrinsic biological characteristics that determine agricultural systems is essential to policy makers. Tax-related policies for GHG mitigating objectives would have a direct impact on farmers' finances or a reduction in the number of stock. Moreover, the best policies may vary depending on the type of system and farming conditions (Neufeldt and Schäfer, 2008). As described before, practices which best reduce GHG emissions may vary between locations (Lovett et al., 2008; Stewart et al., 2009). Thus, it is relevant to consider this biological variation when investigating the best methods for GHG abatement. Practices mentioned as having high GHG reduction and being cost negative, referred to as "win-win" alternatives (Moran et al., 2011) need to be assessed with a more dynamic and holistic approach, where interactions among different components of the systems are taken into account during the simulations. It is relevant to evoke at this point that livestock systems are food providers and therefore vital to feed the expected growing population. International knowledge transfer for improving the efficiency of food production systems will have a direct beneficial effect on global GHG mitigation (Smith et al., 2007). In a global context, this work is intended to contribute to knowledge on reducing the uncertainty over C footprints from complex environments managed for food production. It will help to inform Life Cycle Assessment studies and policy makers in better designing actions for reducing agricultural C footprints.

1.7 Conclusion

In this chapter, the importance of the agricultural sector and in particular beef farming for food production and biodiversity conservation has been addressed as well as its contribution to GHG emissions. Literature regarding the prediction of these gases, modelling approaches adopted, mitigation and measurement techniques were reviewed and gaps in knowledge have been identified. There is a need for studies considering practices for reducing GHG at the whole systems level, mainly for regions such as Scotland with a large proportion of the country relying on semi-natural grassland which should be utilized for food production in a sustainable way. Limitations of available technologies to determine CH_4 emissions from animals on extensive grasslands create uncertainties over the quantification of their C footprint.

The variability associated with grazing behaviour of extensively managed herds has not yet been investigated in CH_4 studies, which would contribute towards reducing the ambiguity of predictions of C budgets from these environments. Methane production is influenced by physiological stage but this effect has not yet been considered on beef farming systems at the whole-farm scale, which vary biologically and contribute to additional variability over the year. Finally, several practices have been reviewed in this chapter concerning the management of different parts of the system. The impact of alternative GHG mitigation options on systems managed at different levels of intensity need further research to fully understand how these practices interact with the rest of the system, and the net emissions resulting from their application. Studying the relative importance of different management alternatives for reducing the C emissions of the system is needed urgently to inform the climate change debate. In particular, potential actions need to be identified to reduce C emissions from upland systems that are compatible with environmental and biodiversity conservation.

1.8 Objectives of the study

The objectives of this thesis were to identify gaps in the knowledge regarding the main factors affecting GHG emissions from beef farming systems; to improve the accuracy of GHG predictions, mainly for upland systems that may utilize semi-natural grasslands which are relevant to the UK and Scotland; and to study the relative importance at the farm-scale of utilizing suggested GHG mitigation options, either on the productivity of the farm, the returns of human-edible food and possible impacts on the biodiversity of vulnerable habitats.

1.9 Thesis outline

In order to achieve these objectives, this work was divided into 4 main parts (chapters) to investigate and provide information on some important gaps in knowledge.

A deterministic model was developed to represent the animal sub-system within a farm and to account for factors affecting the emissions of the main GHGs: CH_4, N_2O and CO_2. A lack of information in the literature was identified regarding the quantification of some relevant animal characteristics that are thought to have a direct impact on CH_4 emissions. This issue was investigated in **Chapter 2** of this thesis. The objectives were to evaluate the impact of a combination of animal characteristics and management conditions on CH_4 outputs, and to illustrate the potential improvement at the farming system level of using a series of specific mathematical models to predict CH_4 from ruminants under different physiological stages and diet types.

Other characteristics of grazing animals such as their natural foraging behaviour are known to differ between breeds and management condition. However, the impact on GHG emissions is unknown, probably due to the difficulty of measurement in experimental studies, and representation in mathematical modelling studies. This issue was addressed in **Chapter 3**. A large dataset on foraging behaviour of free-range suckler cows in hill grasslands was used in a modelling study, to predict the impact of diverse genotypes showing different grazing strategies on the potential CH_4 emissions.

One of the limitations on collecting reliable information from cattle is the disadvantages of some techniques available to measure CH_4 emission. Thus, in **Chapter 4** the use of a Laser Methane Detector (LMD) was evaluated with the objective of assessing its potential application for remote sensing of CH_4 from cattle on their natural environment. In this work, the LMD was evaluated on indoor lactating ewes and finishing steers to evaluate the potential factors affecting future measurements, due to the lack of a full validation process of this device and with the aim of a better understanding of its outputs.

Finally, **Chapter 5** was set up to study GHG mitigation options suggested in the literature from a systemic point of view in an empirical and mechanistic model. This model comprises the results described above with the aim of reducing the uncertainty of CH_4 predictions. It also interacts with the SAC C-calculator (RBU, 2011) to obtain predictions of GHG from the other part of the system (e.g. arable). Alternative management options of a beef breeding-finishing baseline system are compared, considering not only their impact on GHG emissions and productivity, but also the returns of human-edible food and their potential impact on biodiversity conservation programs. The main management options taken into account in the study are extensive vs. intensive systems, pure native breed vs. improved breed, more efficient animals as a result of genetic improvement, length of finishing period (including use of high-concentrate diets), use of additives in diets, use of less fertiliser and use of grass pasture vs. grass/clover mixed sward in a lowland area.

The information generated from this thesis will increase the knowledge and understanding of extensively managed beef production systems in the context of climate change and will contribute valuable information for future research on system analysis and for policy makers, for development of actions to mitigate the environmental impact of these types of systems.

Chapter 2: Physiological stage and methane emissions

Adapted from: Ricci, P., Rooke, J., Nevison, I., Waterhouse, A. 2013. Methane emissions from beef and dairy cattle: quantifying the effect of physiological stage and diet characteristics. Journal of Animal Science, 91:5379-5389.

In this chapter I was responsible for reviewing the literature, building the databases, data analyses and writing of the manuscript.

2.1 Introduction

Globally, greenhouse gas emissions equivalent to nearly 40 Gt of carbon dioxide (CO_2) were emitted in 2004 due to anthropogenic activities, agriculture being responsible for 13.5% of these emissions (IPCC, 2007d). Emissions related to livestock production range from 8 to 10.8% of the global greenhouse gas emissions (O'Mara, 2011). Methane (**CH_4**) from ruminants' enteric fermentation contributes 86 million tonnes per year to the global GHG emissions (Steinfeld et al., 2006), and it also constitutes a loss of efficiency for animal production systems. In the UK, enteric CH_4 represents 2.5% of total greenhouse gas emissions (CCC, 2010). Currently, efforts are being made to identify management options under different farming systems to mitigate CH_4 losses. The influence of factors such as feed quality and intake, and animal characteristics and performance on CH_4 production has been addressed (Ellis et al., 2009; Yan et al., 2009; Grainger and Beauchemin, 2011). However, little effort has been made to differentiate and quantify the effect of physiological stages of animals when predicting CH_4 emissions. As a pertinent example, beef farms comprise animals in distinct physiological stages, often under diverse reproductive and nutritional management. Current farm-scale models do not differentiate between combinations of all of these factors when predicting enteric CH_4 outputs and assume that different categories of animals in a herd fed diverse diets have similar relationships between CH_4 emissions and feed quality and intake (Schils et al., 2007b). Nevertheless, selecting the correct solution at farm level is the key to achieving a net global impact in efficiently reducing greenhouse gases from agriculture (Franks and Hadingham, 2011).

This study sets out to consider the potential gain of using more appropriate equations for different types of animals, diets, and management to predict CH_4 emissions to produce more accurate inventories and reduce the uncertainty of studies considering mitigation options using the advantages of a meta-analysis. Further, a farm system study is used to evaluate and illustrate the scale of potential improvement in accuracy and sensitivity to changes in the prediction equation approach.

2.2 Materials and methods

This work comprises 3 main sections. First, a database of dairy and beef cattle data including measured CH_4 outputs, animal characteristics, and feed quality and intake was built from the literature and analysed to assess the effects of animal and diet features on CH_4 production. Second, models fitted in the first section were validated using an independent dataset and compared with existing models. Finally, the validated model was used to predict CH_4 emissions from a commercially managed beef herd at the Scotland's Rural College (**SRUC**) Beef and Sheep Research Centre, Edinburgh, UK. The IPCC (2006) CH_4 prediction equation was also applied to these data. Both predictions were compared in order to illustrate the impact of applying an improved CH_4 prediction model to actual farm data comprising different animal categories and feed qualities.

2.2.1 Database

A total of 90 published papers containing measurements of CH_4 production from dairy and beef cattle, animal characteristics, feed quality, and feed intake were reviewed. From these, studies were selected based on the availability of more than one mean value per study to account for the variation between studies and measured CH_4 with corresponding estimates of precision (error term). The selection criteria also considered the presence of measured values of the main potential explanatory variables such as DMI, BW, dietary GE, DE, and ME and chemical characteristics of the diet such as OM, CP, NDF, ADF, lignin, fat, and dry matter digestibility (**DMD**). Missing data were obtained from tables of feed composition: NRC (1996; 2001) for American studies and MAFF (1990) for European studies. If unavailable, values were estimated from established prediction equations such as: ME (MJ/d) = DMD x 15.7 (AFRC, 1993). For most studies reviewed, data on non-structural carbohydrates, such as starch and sugar, were unavailable; thus these variables were ignored in the present study. A final database comprising 211 treatment means was compiled from the 38 selected studies where CH_4 had been measured on beef (n = 132 treatment means) and dairy (n = 79) cattle (Tables 2 and 3).

From the 38 studies, information about other potentially relevant factors was extracted and considered for the analysis as categorical factors. These included type of enterprise (beef or dairy); diet type (low or high concentrate); physiological stage (lactating or non-lactating); CH_4 measurement technique (calorimetry, sulphur hexafluoride; **SF_6**); intake (*ad-libitum* or restricted); and whether CH_4 mitigation technologies (e.g. monensin, lipid supplementation, tannins or enzymes, among others) were applied or not (treated or untreated). The type of diet was characterized into 2 categories with high (**HC**) or low (**LC**) concentrates where concentrates constituted more than, or less or equal to 500 g/kg diet (DM basis), respectively. Other potential factors such as feeding level, milk yield, breed, and animal category (i.e. cow, heifer, steer, bull) were not included in the database due to lack of data or inconsistent information across studies.

Table 2. Summary of database of CH_4 outputs (g/d) and categorical factors

	Author	N[1]	Mean ± SE	System	Stage[2]	Feed[3]	Technique[4]	CH_4 reduction[5]	Intake[6]
1	Beauchemin and McGinn (2005)	4	110.7 ± 24.54	Beef	NL	LC, HC	Cal	Treated	Ad lib
2	Beauchemin and McGinn (2006b)	4	150.3 ± 14.28	Beef	NL	LC	Cal	Treated, Untreated	Ad lib
3	Beauchemin and McGinn (2006a)	4	141.5 ± 11.88	Beef	NL	LC, HC	Cal	Treated, Untreated	Rest, ad lib
4	Beauchemin (2007)	4	150.8 ± 11.87	Beef	NL	LC	Cal	Treated, Untreated	Ad lib
5	Belyea et al. (1985)	4	148.4 ± 5.11	Dairy	NL	LC	Cal	Untreated	Rest, ad lib
6	Boadi and Wittenberg (2002)	4	165.3 ± 11.39	Beef, Dairy	NL	LC	SF_6	Untreated	Rest, ad lib
7	Boadi et al. (2002a)	2	95.4 ± 2.50	Beef	NL	LC	Cal, SF_6	Untreated	Ad lib
8	Boadi et al. (2002b)	7	229.2 ± 9.05	Beef	NL	LC	SF_6	Untreated	Ad lib
9	Boadi et al. (2004)	2	77.8 ± 13.54	Beef	NL	HC	SF_6	Untreated	Ad lib
10	Cavanagh et al. (2008)	2	310.5 ± 21.50	Dairy	L	LC	SF_6	Untreated	Ad lib
11	Chaves et al. (2006)	6	151.0 ± 8.35	Beef	NL	LC	SF_6	Untreated	Ad lib
12	Cushnahan et al. (1995)	3	379.8 ± 32.98	Dairy	L	LC	Cal	Untreated	Ad lib
13	Grainger et al. (2009)	3	372.3 ± 36.37	Dairy	L	LC	SF_6	Treated, Untreated	Ad lib
14	Grainger et al. (2010a)	2	470.7 ± 7.92	Dairy	L	LC	SF_6	Treated, Untreated	Ad lib
15	Hindrichsen et al. (2005)	6	379.7 ± 14.83	Dairy	L	LC	Cal	Untreated	Ad lib
16	Hironaka et al. (1996)	8	110.9 ± 9.27	Beef	NL	LC	Cal	Untreated	Rest, ad lib
17	Holter et al. (1986)	5	186.5 ± 7.40	Dairy	NL	LC	Cal	Untreated	Rest
18	Holter et al. (1990)	5	242.7 ± 17.73	Dairy	L	LC, HC	Cal	Untreated	Ad lib
19	Holter et al. (1992)	7	207.6 ± 9.42	Dairy	L	HC	Cal	Untreated	Ad lib
20	McCaughey et al. (1997)	4	195.1 ± 9.71	Beef	NL	LC	SF_6	Treated	Ad lib
21	McCaughey et al. (1999)	2	280.8 ± 14.03	Beef	L	LC	SF_6	Untreated	Ad lib

Continue

	Author	N[1]	Mean ± SE	System	Stage[2]	Feed[3]	Technique[4]	CH_4 reduction[5]	Intake[6]
22	McGinn et al. (2004)	8	165.3 ± 5.77	Beef	NL	LC	Cal	Treated, Untreated	Ad lib
23	McGinn et al. (2006)	8	138.9 ± 7.71	Beef	NL	LC, HC	Cal, SF_6	Treated, Untreated	Rest, ad lib
24	Moe and Tyrrel, (1979a)	3	340.5 ± 13.25	Dairy	L	HC	Cal	Untreated	Ad lib
25	Moe et al. (1973b)	2	194.4 ± 4.89	Dairy	L	HC	Cal	Untreated	Ad lib
26	Moe et al. (1973a)	4	248.2 ± 13.69	Dairy	L	HC	Cal	Untreated	Ad lib
27	Münger and Kreuzer (2006)	18	335.7 ± 18.81	Beef, Dairy	L, N-L	LC	Cal	Untreated	Ad lib
28	Nkrumah et al. (2006)	3	119.1 ± 11.25	Beef	NL	HC	Cal	Untreated	Ad lib
29	Ominski et al. (2006)	8	139.6 ± 6.08	Beef	NL	LC	SF_6	Untreated	Ad lib
30	O'Neil et al. (2011)	4	323.8 ± 30.05	Dairy	L	LC	SF_6	Untreated	Ad lib
31	Pinares-Patiño et al. (2008b)	13	248.3 ± 27.52	Beef, Dairy	L, N-L	LC	SF_6	Untreated	Ad lib
32	Pinares-Patiño et al. (2007)	16	217.1 ± 5.89	Beef	NL	LC	SF_6	Untreated	Ad lib
33	Reynols and Tyrrel (2000)	10	209.2 ± 14.59	Beef	L, N-L	LC	Cal	Untreated	Ad lib
34	Reynolds et al. (1991)	4	103.1 ± 16.11	Beef	NL	LC, HC	Cal	Untreated	Ad lib
35	Tyrrell et al. (1992)	8	95.4 ± 3.20	Beef	NL	LC	Cal	Untreated	Ad lib
36	van Dorland et al. (2007)	6	431.7 ± 9.81	Dairy	L	LC	Cal	Untreated	Ad lib
37	Varga et al. (1990)	4	125.6 ± 9.95	Beef	NL	LC	Cal	Untreated	Ad lib
38	Waldo et al. (1997)	4	165.7 ± 5.84	Beef	NL	LC	Cal	Untreated	Ad lib

[1]N = number of treatment means on study.

[2]Physiological stage: lactating (L) or non-lactating (NL).

[3]Feed: low concentrates (LC) or high concentrates (HC).

[4]Methane measurement technique: calorimetric (Cal) or Sulphur hexafluoride (SF_6).

[5]CH_4 reduction: use (treated) or not (untreated) with methane reduction treatments (such as, monensin; fumaric acid, oils; high-concentrates, tallow, enzymes, or yeasts).

[6]Level of intake: Restricted (Rest) or *ad libitum* (ad lib).

Table 3. Summary of descriptive statistics for variables present in the assembled database for model development (n = 215)

Variable[1]	Mean	SD	Min	Max	CH_4, g/d[2]	
					r	*P*-value
CH_4, g/d	216.2	101.02	62.1	478.7	-	-
CH_4, g/kg DMI	20.6	4.58	6.4	33.4	-	-
MBW, kg	95.9	20.56	61.0	131.1	0.643	<0.001
DMI, kg/d	10.8	4.77	3.6	20.1	0.837	<0.001
GEI, MJ/d	198.7	85.71	66.7	373.7	0.840	<0.001
DEI, MJ/d	133.9	63.83	41.1	265.4	0.831	<0.001
MEI, MJ/d	109.5	54.84	30.7	237.4	0.800	<0.001
FP, %	79.5	25.29	9.0	100.0	0.046	0.51
CP	172.4	34.37	52.0	290.0	0.203	0.003
NDF	444.3	124.87	127.0	731.0	0.086	0.21
ADF	270.4	88.18	35.0	464.0	-0.040	0.57
Lignin	52.8	26.53	10.2	154.0	-0.220	0.001
Fat	31.6	12.87	16.0	90.0	-0.105	0.13
DMD	627.0	76.46	402.9	813.0	0.186	0.007

[1]g/kg DM, unless otherwise state; MBW = metabolic body weight; GEI = GE intake; DEI = DE intake; MEI = ME intake; FP: forage proportion; DMD = DM digestibility.
[2]Pearson correlation coefficient and *P* values between variables and CH_4 (g/d).

2.2.2 Validation

Validation of the model obtained in the first part of this chapter was performed with an independent set of data from 18 published studies and 2 studies from SRUC (Edinburgh, UK) of respiration chamber CH_4 outputs from individual steers fed HC (92% concentrates, n = 34) and LC (n = 34, Rooke et al., 2013) and LC fed non-lactating beef cows (n = 41, Duthie et al., 2013). Some studies that were excluded from the calibration dataset due to lack of essential information (e.g. SEM) but contained enough information to utilize the resulting prediction model were included in the validation dataset. The validation dataset contained 63 treatment means from published studies and a total of 109 individual animal observations from SRUC studies (Table 4).

Table 4. Summary statistics of observed CH_4 (g/d) data for each of the combinations between physiological stage and feed type used for validation of resulting models. Dataset contains mean of treatments from the literature and individual animal observations from Scotland's Rural College (SRUC) studies

	Author	Stage[1]	Feed[2]	N[3]	Mean	Min	Max	SD
1	Chung et al. (2012)	L	LC	3	507	471	545	37.0
2	Coppock et al. (1964)	L	LC, HC	3	305	292	315	11.9
3	Estermann et al. (2002)	L	LC	2	413	395	431	25.4
4	Grainger et al. (2010b)	L	LC	8	466	429	534	41.0
5	Moe and Tyrrel (1977)	L	HC	6	236	153	323	82.9
		NL	LC	1	147	-	-	-
6	O'Neil et al. (2012)	L	LC	3	380	349	406	28.8
7	Sauer et al. (1998)	L	LC	8	422	369	453	23.4
8	Tyrrel and Moe (1972)	L	LC, HC	2	276	223	329	74.8
9	Moe and Tyrrel (1979a)	NL	HC	3	159	157	161	2.4
10	Vlaming et al. (2008)	NL	LC, HC	2	147	124	170	32.2
11	Birkelo et al. (1986)	NL	LC	2	76	63	89	18.7
12	Boadi and Wittenberg (2002)	NL	LC	6	166	138	207	32.0
13	Hegarty et al. (2007)	NL	HC	1	180	-	-	-
14	Hulshof et al. (2012)	NL	LC	2	105	85	125	28.3
15	Jiao et al. (2013)	NL	LC	2	94	91	96	4.2
16	Okine et al. (1989)	NL	LC	1	110	-	-	-
17	Pedreira et al. (2012)	NL	LC	4	135	113	166	23.4
18	Shinkai et al. (2012)	NL	LC	4	178	137	221	37.8
	SRUC studies							
19	Rooke et al. (2013)	NL	LC, HC	68	174	78	333	48.9
20	Duthie et al. (2013)	NL	LC	41	217	146	349	48.6
	Overall	L	HC	8	244	153	323	75.7
			LC	27	426	292	545	62.4
		NL	HC	39	146	78	233	38.3
			LC	98	194	63	349	52.9
	Total			172	222	63	545	105.4

[1]Stage: physiological stage defined as either lactating (L) or non-lactating (NL).
[2]Feed: feed type defined as high (HC) or low concentrates (LC) where concentrates constituted more than, or less or equal to 500 g/kg diet (DM basis), respectively.
[3]N: number of treatment means on study; individual animal observations in 19 and 20.

The CH_4 prediction ability of the resulting model from this study was compared with the IPCC (2006) model (Equation 1), as this is widely applied (e.g. Foley et al., 2011; Weiss and Leip, 2012) in whole-farm modelling exercises to account for CH_4 estimation in a systemic approach:

$$CH_4\ (g/d) = ((GEI \times Ym) \times 1000\ (g/kg))/55.65(kg/MJ) \qquad (Eq.\ 1)$$

where GEI represents the GE intake of the diet (MJ/d) and Ym is the CH_4 emission factor (i.e. the proportion of GEI lost as CH_4, with a value of 3 ± 1 or 6.5 ± 1% for diets containing above or below 90% concentrates, respectively). The Ym values are rough estimates of CH_4 yields made by IPCC (2006), which are based on general feed and animal characteristics found in developed and developing countries. However, these authors highlight the need for better estimates of Ym for diverse livestock and feed types used in different countries.

2.2.3 Simulation of beef herd CH_4 emissions

The performance of the equations from this study on predicting CH_4 outputs from an actual beef herd was compared against existing equations in the literature. Monthly BW and BW change (**BWC**) data from 20 Limousin x Aberdeen Angus cows with calves, 20 Aberdeen Angus x Limousin growing steers and heifers (from weaning to finishing) and 36 finishing steers (from a different herd) obtained in 2011 at SRUC were used for comparing predictions (Table 5). Energy requirements, DMI, and GEI of cows, calves, and steers were predicted from actual BW, BWC, predicted milk yield and feed energy values based upon AFRC (1993).

Cows on different systems each passed through pregnant, lactating, and dry phases over the annual production cycle. Cows calved during the spring (from end of March to end of May) and grazed from March to September either hill (**HG**, n = 11) or lowland grassland (**LG**, n = 9), with a mean BW of 653 ± 27.9 and 686 ± 29.6 kg, respectively. As measurements of actual digestibility of intake for grazed pastures were unavailable, monthly DMD of LG and HG from the literature were used as follows. The HG was dominated by *Agrostis capillaris*, *Festuca rubra* and *Nardus stricta*, hence an annual average energy content of 7.3 ± 1.07 ME (MJ/kg DM ± SD) was assumed based on data from similar hill grasslands in the UK described by Armstrong et al. (1986). Similarly, as LG was dominated by *Lolium perenne* a mean ME of 10.0 ± 1.09 MJ/kg DM over the year was used, as described by Wallis de Vries and Daleboudt (1994). After the grazing period, calves were weaned with a mean BW of 208 ± 4.1 kg (mean ± SE). Cows (n = 20) and weaned calves (n = 20) were fed indoors throughout the winter with a low concentrate (**LC**) diet consisting of 40% grass silage, 35% barley silage, 15% barley grain, and 10% maize distillers dark grains (DM basis), with an estimated diet ME of 9.9 MJ/kg DM. In May, steers entered the finishing period weighing 516 ± 13.1 kg on average, and were fed either LC (n = 18) or high concentrate diets (**HC**, n = 18) until October when they reached slaughter weight (639 ± 14.5 kg). The LC diet was similar to the over-wintering diet, whereas the HC diet consisted of 12% straw, 68% barley grain, and 20% maize grain (DM basis) and estimated diet ME of 12.8 MJ/kg DM. Chemical composition of LC and HC diets was obtained from the literature (MAFF, 1990).

Table 5. Monthly feed allocation, physiological stage and body weights of cows grazing either Hill or Lowland grassland, and monthly body weights of weaned calves and finishing steers fed indoor diets.

Month	Cows				Weaned	Steers	
	Feed	Stage	Hill	Lowland	calves	LC	HC[3]
Jan	LC[1]	NonLac[2]	645 ± 102	700 ± 86	322 ± 38		
Feb	LC	NonLac	656 ± 113	718 ± 86	350 ± 41		
Mar	LC	NonLac	654 ± 113	709 ± 84	378 ± 44		
Apr	Grazing	Lac	658 ± 96	689 ± 84	406 ± 47		
May	Grazing	Lac	661 ± 80	669 ± 85		522 ± 57	510 ± 53
Jun	Grazing	Lac	665 ± 67	649 ± 87		567 ± 58	554 ± 52
Jul	Grazing	Lac	661 ± 80	669 ± 85		600 ± 58	589 ± 54
Aug	Grazing	Lac	663 ± 89	681 ± 92		627 ± 58	617 ± 53
Sep	Grazing	Lac	656 ± 91	685 ± 90		642 ± 57	634 ± 45
Oct	LC	NonLac	647 ± 91	702 ± 103	236 ± 30	638 ± 49	641 ± 38
Nov	LC	NonLac	641 ± 93	689 ± 96	269 ± 32		
Dec	LC	NonLac	635 ± 95	675 ± 89	298 ± 39		

[1]LC: Low-concentrate diet.
[2]NonLac: Non-lactating; Lac: lactating.
[3]HC: High-concentrate diet.

Methane emissions were predicted monthly for each individual cow, calf, and steer. Monthly and annual average and accumulated values of CH_4 and CH_4 proportional to GEI were compared with predictions from the IPCC (2006) equation. The impact of using the new CH_4 prediction model at the farm level was assessed as follows. Methane outputs from a series of simulated beef systems using the data from above were predicted with both the new model and IPCC model. The core systems consisted of 100 cows, 90 weaned over-wintering calves and 45 finishing steers. Four systems were compared - cows grazing either HG or LG during the summer and fed LC during winter with weaned calves, and finishing steers fed either HC or LC. Methane predictions from each of the systems were obtained by multiplying monthly average CH_4 from cows, calves, and steers and their number in the simulated herd.

2.2.4 Statistical analysis

The ability of potential explanatory variables to predict CH_4 outputs from the calibration database was tested by fitting random coefficients models by Restricted Maximum Likelihood using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). Potential explanatory variables were first screened as sole predictors of CH_4 and not considered further when the associated probability value exceeded 0.25. As data were compiled from different studies, study was considered as a random effect. In order to account for differing precision in observed means, models were fitted using weights proportional to the reciprocals of their variances (St-Pierre, 2001). It was assumed in the present study that the variation in observed CH_4 is lower within trials than between trials. Correlations between variables were estimated using the CORR procedure of SAS. The random coefficients prediction models were built up using a process analogous to the stepwise selection process of adding and removing individual explanatory variables one at a time based on addition of the most highly significant term ($P < 0.05$) not already in the model and removal of terms no longer statistically significant.

The random coefficient model fitting described above was repeated with each of GEI, DMI, DEI, and MEI included as the first term since they were highly correlated with each other. From these, the best-fit model was selected by comparing the goodness-of-fit between predicted and observed CH_4 from the calibration dataset, assessed by the adjusted coefficient of determination (**AdjR²**) and the standard error of calibration (**SEC**, Equation 2):

$$\text{SEC} = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-p-1}} \qquad \text{(Eq. 2)}$$

where y_i and $\hat{y}_i$ represent observed and predicted CH_4 of the observation i (i = 1, 2, … n); n denotes total observations on the calibration dataset (n = 215) and p the number of fixed effects parameters in the model (in all cases p = 5, Table 6). Predicted values were obtained by using the OUTP option of the MODEL statement, which gave predictions including random effects.

The ability of the resulting model to predict observed CH_4 from an independent validation dataset was compared with the IPCC (2006) model using the standard error of validation (**SEV**, Equation 3), $AdjR^2$ and the Lin's Concordance correlation coefficient (**CCC**, predictive ability increases as it approaches a value of 1).

The SEV was estimated as:

$$\text{SEV} = \sqrt{\frac{\sum(y_k - \hat{y}_k)^2}{m-1}} \qquad \text{(Eq. 3)}$$

where y_k and $\hat{y}_k$ represent observed and predicted CH_4 of the observation k (k = 1, 2, … m) and m denotes total observations on the validation dataset (m = 172). Predicted values were obtained using the OUTPM option of the MODEL statement, which gave predictions considering only fixed effects of the model.

The CCC combines the precision measurement of Pearson correlation coefficient (r) with a bias correction factor (**C_b**, the closer to 1 the better), a measurement of accuracy, in terms of the deviation from the origin and slope of a 45 degree line when comparing predicted vs. observed values (Lin, 1989). The Lin's Concordance Coefficient test of GenStat (11th edition) was used to estimate the CCC.

Results of the beef herd CH_4 predictions are presented in the form of means ± standard errors. These standard errors do not include uncertainty in the fitted model but cover variability in predictions due to differences in actual individual BW and performance data.

2.3 Results and discussion

The resulting database comprised diets of widely differing energy content and types of animals under different farming systems (Tables 2 and 3).

2.3.1 Variable selection

Methane outputs (g/d) were correlated with most of the candidate explanatory variables ($P < 0.05$; Table 3). However, intake related variables (DMI, GEI, DEI, and MEI) and metabolic body weight ($BW^{0.75}$, **MBW**) had stronger correlations with CH_4 than diet chemical variables. Descriptive statistics for variables in the assembled database are presented in Table 3. Individually, intake related variables explained a substantial proportion of the variation in observed CH_4. Preliminary screening excluded forage proportion (forage DM: total DM, FP, $P = 0.64$) and ADF ($P = 0.28$) from the selection process. Intake relative to MBW was not as important as considering both variables separately during the variable selection process. In agreement with others, intake, either as energy or DM, was the most highly correlated variable with CH_4 (Boadi and Wittenberg, 2002; Hammond et al., 2009). Dry matter intake was non- and weakly correlated with NDF and ADF (r = -0.09, -0.22; $P = 0.20$, 0.001; respectively).

In all cases, CH_4 showed a linear relationship with intake-related variables as quadratic terms were non-significant ($P > 0.25$). By contrast, Bell et al., (2009) evaluating data exclusively from high-yielding dairy cows, found a non-linear relationship between CH_4 outputs and DMI. Although information on milk yield would be relevant to consider the impact of animals' performance on CH_4 estimates, data on milk yield, BWC or feeding level in CH_4 studies were scarce.

After screening categorical factors, CH_4 measurement technique ($P = 0.38$) and CH_4 reduction treatment ($P = 0.30$) were excluded from the analysis and candidate factors included in the model were enterprise, physiological stage, diet type, and intake restriction. When adding factors to the model, the final step of the algorithm indicated type of enterprise (P = 0.65) and intake restriction (P = 0.26) had no significant effects on the model.

Finally, 4 different models based upon either DMI, GEI, DEI or MEI were obtained (Table 6), as collinearity was observed between these variables ($r > 0.97$; $P < 0.001$). Although all models showed a good fit with observed CH_4, models based on either GEI or DMI and including diet type, physiological stage and the simple interaction between them showed slightly better goodness-of-fit compared with models based on either DEI or MEI and explained most of the variation in observed CH_4 ($AdjR^2$ = 96.1%, $P < 0.001$, Table 6). Significant interactions between factors and continuous variables produced a set of different equations with different slopes for each combination of diet type and physiological stage. To my knowledge, this approach for prediction of CH_4 production has not been reported in the literature. Grainger et al. (2007) compared the relationship between CH_4 and DMI from different countries and mentioned a difference in the slopes of the regression line. According to the results obtained in the present study, differences in slopes can be attributed to varying physiological stages and feeding management.

Table 6. Methane prediction models (coefficients ± SE) obtained from the calibration dataset based on each of the four variables (GEI, DMI, DEI and MEI) which individually described most variation in methane output

	CH_4 prediction models, g/d[1]	SEC[2]	AdjR[2 3]
1	74.34(±15.69) + 0.57(±0.11) x GEI - 10.61(±22.77) x Feed - 69.67(±39.63) x Stage - 0.22(±0.10) x GEI x Feed + 0.57(±0.18) x GEI x Stage	20.02	96.07
2	79.87(±15.74) + 9.95(±1.97) x DMI - 15.15(±21.92) x Feed - 74.48(±40.59) x Stage - 3.67(±1.79) x DMI x Feed + 10.90(±3.33) x DMI x Stage	20.01	96.08
3	88.41(±14.96) + 0.75(±0.15) x DEI - 19.28(±23.14) x Feed - 39.19(±36.19) x Stage - 0.291(±0.15) x DEI x Feed + 0.69(±0.25) x DEI x Stage	20.50	95.88
4	98.56(±25.15) + 1.19(±0.16) x MEI - 44.80(±40.77) x DMD + 133.06(±86.27) x Feed + 52.16(±15.31) x Stage - 282.57(±125.17) x DMD x Feed	21.27	95.57

[1]GEI = GE intake (MJ/d); Feed = feed type (low concentrates (≤ 500 g/kg DM diet) = 0 or high concentrates (> 500 g/kg DM diet) = 1); Stage = physiological stage (non-lactating = 0, lactating = 1); DEI = DE intake (MJ/d); MEI = ME intake (MJ/d); DMD = DM digestibility (kg/kg DM). Minimum value of intake-related variables adopted for model fitting as described in Table 2.
[2]SEC: standard error of calibration.
[3]AdjR^2: Adjusted coefficient of determination

2.3.2 Validation and comparison with current equations

The present models based on GEI and DMI (referred to hereafter as **NewEqGEI** or **NewEqDMI**, respectively) were applied to an independent dataset (n = 172, Table 3) to validate the models and to compare them with the IPCC (2006) model (referred hereafter as **IPCC**). Results from the validation test are presented in Table 7 and Figure 4. Good agreement was observed for the 3 models compared. The NewEqGEI model showed the lowest SEV and the highest r and CCC. In comparison, IPCC showed slightly higher C_b than NewEqGEI. The parameter C_b indicates the degree of deviation of the model best-fit line compared with the concordance line between observed and predicted (45 degree line). Deviations from accuracy (location-shift) can be potentially corrected, but failure to produce precise (e.g. R^2) estimations is a non-remediable fault. The NewEqGEI model had the highest $AdjR^2$. Overall, the NewEqGEI and NewEqDMI models showed good agreement with observed CH_4 and explained 10 and 8% additional variation in observed CH_4, respectively than IPCC. Extrapolation of the model was required for 8 observations in the validation dataset. However, removing these observations did not change the trend of the results observed previously. These results indicate that for whole-farm CH_4 estimation, although IPCC is a good model, physiological stage explains additional variation to diet type and intake together.

Compared with the IPCC model, this study demonstrates the benefit of including information on animal characteristics. By adding a term related to physiological stage, type of diet and their interaction with continuous variables, NewEqGEI improved the performance of CH_4 predictions. Although IPCC has shown to be a good model for performing CH_4 budgets from a whole-farm holistic approach, the new model helped to improve the precision of CH_4 estimates over a wide range of physiological states and diet types at a farm level. It is clear that there is value in differentiating between diet types and physiological stage and their interaction with continuous variables related to feed quality and intake to explain most of the variation observed in CH_4 emissions.

Table 7. Validation of best-fit models from the present study and their comparison with current equation mentioned by IPCC (2006)

Model[1]	**SEV**[2]	**AdjR^2** [3]	**r**[4]	**C_b**[5]	**CCC**[6]
IPCC	56.46	74.5	0.864	0.993	0.858
NewEqGEI	44.07	84.7	0.921	0.983	0.905
NewEqDMI	46.31	82.9	0.911	0.985	0.897

[1]IPCC referrers to CH_4 (g/d) = ((GEI x Ym) x 1000)/55.65), where Ym = 0.03 or 0.065 for diets with more or less than 90% concentrates (IPCC, 2006). NewEqGEI and NewEqDMI as described in Table 6.
[2]SEV = standard error of the validation.
[3]$AdjR^2$ = coefficient of determination adjusted by the number of parameters in the model.
[4]r = correlation coefficient.
[5]C_b = bias correction factor.
[6]CCC = concordance correlation coefficient.

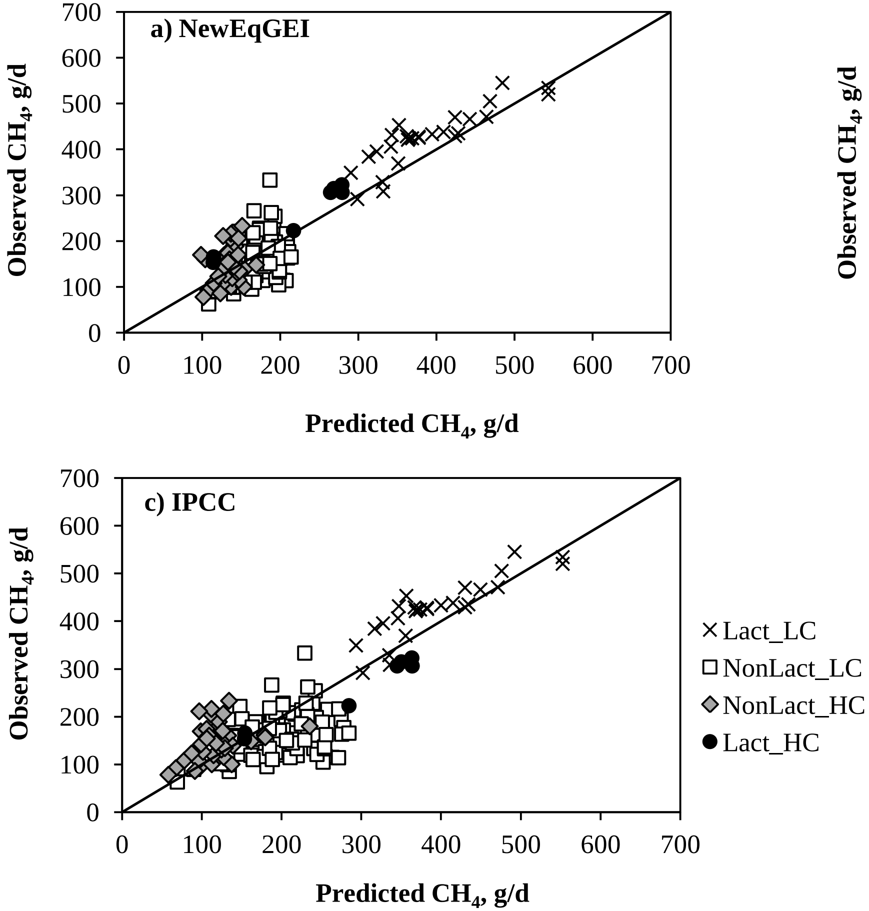


Figure 4. Observed CH_4 (g/d) from the validation dataset vs. predicted with a) NewEqGEI, b) NewEqDMI as shown in Table 6, and c) IPCC (2006) Tier 2 CH_4 (g/d) = ((GEI x Ym) x 1000)/55.65), where Ym = 0.03 or 0.065 for diets with more or less than 90% concentrates (IPCC, 2006). Methane data from different physiological stage and diet type as explained in Table 6

2.3.3 Beef herd CH_4 simulations

The validated model based upon GEI (NewEqGEI, Table 8) and the IPCC equation were applied to individual animal performance and diet quality data from SRUC to simulate system CH_4 outputs. Beef enterprise data were used, as these farm systems simultaneously carry cattle in different physiological stages consuming different diets. Although this simulation exercise compared 2 prediction equations with no actual CH_4 measurements, it demonstrated the ability of the different equations to capture the effect on CH_4 outputs of the shifts from the lactating to non-lactating state and the different diets fed. The impact of the equations (NewEqGEI vs. IPCC) on estimated monthly or annual mean CH_4 outputs (Figure 5) differed between physiological stages. Energy lost as CH_4 (% GEI) predicted by NewEqGEI averaged 6.1 ± 0.22% across all animal categories and diet combinations. For individual animal and diet combinations CH_4, energy losses ranged from 4.1 to 8.1% of GEI and these differences are now described and discussed.

Table 8. Individual prediction equations (mean of parameters ± SE) for methane output (CH_4, g/d) used in Beef Herd Methane Simulations. Equations were derived from model based on individual physiological stage, feed type and GE intake (GEI, MJ/d). (CH_4 (g/d) = 74.34 + 0.57 x GEI - 10.61 x Feed - 69.67 x Stage - 0.22 x GEI x Feed + 0.57 x GEI x Stage)

Stage	Diet[1]	Estimates ± SE of CH_4, g/d					
		Intercept			GEI, MJ/d		
Lactating	LowConc	4.67	±	55.32	1.138	±	0.283
	HighConc	-5.94	±	78.09	0.915	±	0.386
Non-Lactating	LowConc	74.34	±	15.69	0.573	±	0.106
	HighConc	63.73	±	38.46	0.350	±	0.209

[1]Diet = LowConc = low concentrates (≤ 500 g/kg DM diet); HighConc = high concentrates (> 500 g/kg DM diet)

As demonstrated in the previous section, the IPCC (2006) equation produced good estimates of observed CH_4. Therefore, although small, some differences were observed on predicted CH_4 between equations. Despite the different nutritional values of HG and LG, cows grazing HG and LG performed similarly. Therefore, due to the lower digestibility of HG, cows grazing HG were calculated to have higher GEI than LG cows over the year (205 ± 12.9 vs. 165 ± 10.1 MJ/d). Values of intake from cows fed low quality diets look higher than expected. As intake values were back-calculated from actual performance data, the digestibility used for this simulation may have not represented what the cows selected during grazing. Using DMD from other studies of similar Hill and Lowland grasslands could explain a mismatch between the potential energy content of the diet from the literature and the actual animal performance measured on farm. Moreover, cows in the HG may have been able to select a better quality diet from within the available herbage, as the stocking rate in the HG was much lower than in the LG. Digestibility values from the literature had to be used as original data from sampled grass biomass was unavailable, as was actual intake and digestibility. Digestibility values available for the HG were obtained from cuts at ground level, which may differ from the quality of the selected forage. Therefore, these results reflect the lack of accurate information to simulate the GHG emissions from animals grazing under heterogeneous environments, and contributing uncertainty on the total carbon inventories.

When predicted with NewEqGEI, lactating cows grazing HG lost 6.48 ± 0.09% of their GEI as CH_4 and 6.72 ± 0.16% for LG cows. These GE losses compare with the value of 6.5% used by IPCC and for NewEqGEI CH_4 loss ranged from 6.4 to 7.9% GEI from both type of grasslands. During the indoor feeding period with LC diets average CH_4 outputs estimated with either NewEqGEI or IPCC were similar as the 6.54 ± 0.25% of GEI lost as CH_4 predicted by NewEqGEI was not different from the IPCC value (6.5%). However, larger ranges from 5.1 to 8.1% GEI lost as CH_4 were observed in non-lactating cows when applying the NewEqGEI. These results show that IPCC (2006) equation could under-estimate CH_4 from cows with low GEI and over-estimate CH_4 from cows with high GEI. A wide range of data was used to fit the NewEqGEI, where no significant relationship was observed between GEI and quality of the diet, reflecting the wide range of diets where high GEI was recorded. A flatter response of energy lost as CH_4 to changes in GEI was observed for lactating compared with non-lactating cows. This was also observed in the dataset used to fit the equations, suggesting the need of studies quantifying CH_4 emissions from lactating cows of varying performance fed low quality forages that are common in more extensive rangeland based systems.

Annual mean CH_4 predicted by NewEqGEI was 3% lower than IPCC for both HG (7.0 ± 0.33 vs. 7.2 ± 0.45 $kg \cdot mo^{-1} \cdot cow^{-1}$; 2.6 $kg \cdot yr^{-1} \cdot cow^{-1}$ less CH_4 than IPCC) and LG cows (5.6 ± 0.25 vs. 5.8 ± 0.35 $kg \cdot mo^{-1} \cdot cow^{-1}$; 2.4 $kg \cdot yr^{-1} \cdot cow^{-1}$ less CH_4 than IPCC). The ability of the 2 models to predict differences in CH_4 outputs for the different grassland qualities in HG and LG was also compared. Although there were small differences on CH_4 loss between HG and LG, during the 7 mo grazing period, cows on HG produced 31 and 34% more CH_4 than cows grazing LG when predicted with NewEqGEI (61 ± 3.0 vs. 42 ± 2.3 kg) and IPCC (63 ± 3.3 vs. 41 ± 2.9 kg), respectively. Hence, NewEqGEI predicted 3% less differences between feed quality than IPCC. Overall while CH_4 outputs from lactating cows predicted by the 2 equations were similar, NewEqGEI predicted in average 7% lower CH_4 emissions from non-lactating cows than IPCC (2006) equation. Therefore, it is likely that IPCC overestimates actual CH_4 outputs from animals fed lower quality diets, as IPCC does not account for the lower losses of CH_4 energy as a proportion of GEI.

Methane emissions from pre-weaned calves were not predicted, as predicted GEI from forage (from 2.1 to 62 MJ/d) were out of the range of values for which NewEqs were developed (i.e. involve extrapolation, Table 3). Once calves were weaned they were fed LC between October and April. The NewEqGEI predicted similar CH_4 outputs to IPCC over this period from October (4.2 ± 0.13 vs. 4.1 ± 0.26 $kg \cdot mo^{-1} \cdot calf^{-1}$) to April (4.8 ± 0.14 vs. 5.3 ± 0.28 $kg \cdot mo^{-1} \cdot calf^{-1}$) and not unexpectedly energy lost as CH_4 predicted with NewEqGEI averaged 6.52 ± 0.22% of GEI, similar to IPCC.

The greatest difference between equations was observed for the indoor finishing steers when LC and HC diets were used (Figure 5b). For HC diets used during this period (92% concentrates) a Ym value of 0.03 was used in the IPCC equation (IPCC, 2006). For steers fed HC, NewEqGEI predicted 28% higher CH_4 than IPCC (3.6 ± 0.09 vs. 2.6 ± 0.14 $kg \cdot mo^{-1} \cdot steer^{-1}$, Figure 5b), whereas for LC fed steers NewEqGEI predicted 25% less CH_4 than IPCC (6.4 ± 0.32 vs. 8.6 ± 0.64 $kg \cdot mo^{-1} \cdot steer^{-1}$, Figure 5b). In these cases, NewEqGEI predicted higher CH_4 yields from steers fed HC (4.25 ± 0.13%) and lower CH_4 yields for those fed LC (5.03 ± 0.12%) than the 3 and 6.5% suggested by IPCC (2006), respectively.

The NewEqGEI and IPCC equations were also applied to whole-herd simulated systems. Annually NewEqGEI predicted 7% less CH_4 than IPCC from HG cows with steers fed LC (13.0 ± 0.57 vs. 13.9 ± 0.88 t/yr) and 7% less from LG cows with LC fed steers (11.2 ± 0.48 vs. 12.0 ± 0.79 t/yr). However, NewEqGEI predicted similar total annual CH_4 than IPCC from systems with HC fed finishing steers and both HG cows (12.2 ± 0.51 vs. 12.3 ± 0.75 t/yr) and LG cows (10.4 ± 0.42 vs. 10.4 ± 0.66 t/yr), as the lower CH_4 estimates of NewEqGEI form cows were counterbalanced with higher predicted CH_4 from finishing animals fed HC, compared to IPCC (2006) equation. Monthly difference between equations estimates of total CH_4 of all the systems varied from -104 to 191 kg $CH_4 \cdot mo^{-1}$, or from -12 to 16% (IPCC - NewEqGEI). In terms of carbon dioxide equivalents (CO_2eq; 25 times CH_4), differences per month between equation estimates ranged from -2.6 to 4.8 t $CO_2eq \cdot mo^{-1}$, whereas per year differences ranged from -0.37 to 23.7 t $CO_2eq \cdot yr^{-1}$. This result highlights the benefit of using a more adequate model to predict CH_4 emissions which is sensitive to varying GEI over the year according to changes in energy requirements of different animal categories to reduce the uncertainty of carbon budgets.

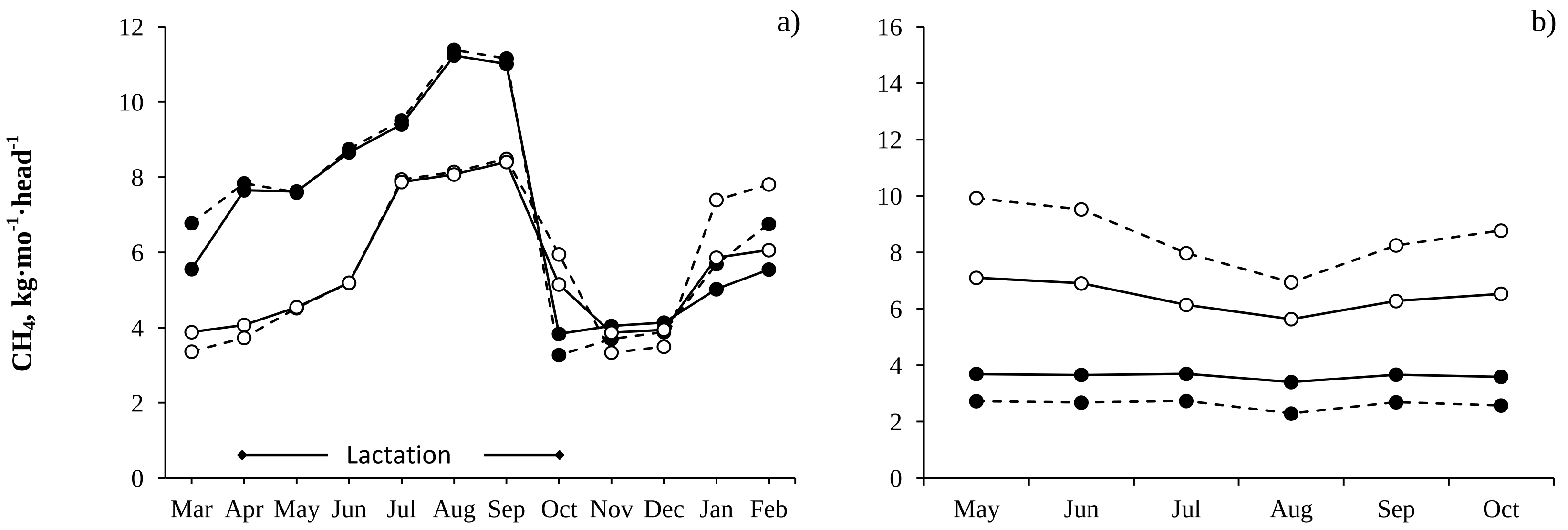


Figure 5. Mean methane outputs (CH_4) predicted with the equation proposed by IPCC (2006, dashed line) or new equations based on GEI (described in Table 8, solid line) from (a) cows fed hill (closed circle, n = 11) or lowland (open circle, n = 9) grasslands and (b) steers fed high (closed circle, n = 18) or low (open circle, n = 18) level of concentrates

2.4 Conclusion

This study has demonstrated the biological impact of physiological stage on CH_4 predictions in cattle. Significantly different slopes of the relationship between GEI and CH_4 were found for a range of combinations of physiological stage and diet type. The current IPCC (2006) equation provided good estimates of CH_4 emissions from a range of animal types, but a multiple equation approach described for the first time in this study provides a higher quality of prediction across a range of important animal and diet factors. A model based on GEI, physiological stage and diet type improved the precision of CH_4 predictions. When applied to observed whole-farm data from a beef herd as predictors, the standard IPCC equation tends to produce higher estimates of CH_4 outputs from non-lactating cows and finishing steers fed LC, and lower estimates of CH_4 from steers fed HC based diets, compared with the new approach. Over the year, using an improved model to predict CH_4 has an impact on the final C budget of the whole-farm, decreasing predicted enteric CH_4 by up-to 24 t $CO_2eq \cdot yr^{-1}$, depending on the type of system. Obtaining more reliable predictions of CH_4 outputs in farm-scale models and in national inventories would help to reduce the uncertainty of mitigation planning studies and cost/benefit analyses.

Chapter 3: Grazing behaviour and methane emissions

Adapted from: Ricci, P., Umstätter, C., Holland, J. P., Waterhouse, A. 2014. Does diverse grazing behavior of suckler cows have an impact on predicted methane emissions? Journal of Animal Science, 92:1234-1244.

In this chapter I was responsible for the data processing, designing and running the model, data analysis and writing of the manuscript.

3.1 Introduction

Grasslands cover approximately 30 to 40% of the earth's surface (White et al., 2000) (Reid et al., 2004) and provide the opportunity to raise 30% of the total livestock population, which contributes 25% of the total meat production from ruminant species (McLeod, 2011). There is considerable uncertainty in the prediction of methane (**CH_4**) emissions from extensively managed ruminants on rangelands (Lassey, 2008). Thus, understanding factors that can improve the accuracy of CH_4 predictions from these environments are critical for realistic inventories of emissions and for identifying routes for mitigation at farm, national, and global levels.

Various cattle breeds of diverse characteristics are used in cow-calf breeding systems (Roughsedge et al., 2001), which can differ in CH_4 emissions under controlled conditions (Estermann et al., 2002). Previous studies have mentioned breed differences in foraging behaviour of cattle on rangelands (Funston et al., 1991; Hessle et al., 2008), which could lead to different use of the available energy. It is known that diurnal grazing patterns affected CH_4 production (Lockyer and Champion, 2001; Dengel et al., 2011). However, the capacity of different breeds to alter their diet, its digestibility or to modify their energy expenditure through different activity patterns and vegetation selection has not yet been considered in CH_4 evaluations. Studies involving grazing animals are usually carried out using homogeneous pastures (McCaughey et al., 1999; Lockyer and Champion, 2001; Allard et al., 2007; Dengel et al., 2011) minimizing the foraging selection process. Due to the difficulty of measuring CH_4 in hill extensive environments, this study aims for the first time to assess in a modelling exercise the scale of potential differences in predicted CH_4 emissions as a result of these factors. This was done by utilizing actual data from a large scale study of grazing behaviour among genotypes of free-range beef cows-calves on semi-natural hill vegetation.

3.2 Materials and methods

3.2.1 Database

A database from a large scale 4 year study of grazing behaviour (Umstätter et al., 2009) containing monthly BW and performance (BW change, **BWC**) of lactating, pregnant spring calving cows and their calves was used in this study. This experiment was ethically reviewed and approved by the SRUC Animal Experiment Committee. This database contains information on horizontal and vertical movements measured on cows by Global Positioning System (GPS) collars (AgTrex BlueSky Telemetry, Aberfeldy, Scotland). Horizontal referred to movements in the x and y plane, whereas vertical referred to movements in the z plane. The GPS collars had integrated activity sensors, which measure minimum and maximum pitch and roll tilt. More details of the methodology can be found in Umstätter et al. (2008). The activity sensors enable characterization of total hours of active and inactive time during the day (considering grazing, drinking, grooming and walking as active time; and lying and standing inactive, while sleeping or ruminating, as inactive time) based on the methodology developed for sheep by Umstätter et al. (2008). This information was collected from 3 genotypes of very divergent size and production characteristics: Aberdeen Angus cross Limousin (**AxL**, n = 15) known as a typical crossbred suckler cow type, Charolais (**CHA**, n = 15) a large sized cow viewed in the UK as suited to more intensive systems, and Luing (**LUI**, n = 15) a typical hardy hill cow believed to be well adapted to hill grasslands in Scotland.

3.2.2 Vegetation, activity and diet selection

Performance and activity data were collected from lactating cows of the 3 genotypes grazing extensive, semi-natural hill grassland and heath during summer periods (from July to September) over 4 consecutive years (2007 to 2010), with a mean stocking rate of 0.23 cow-calf per ha. The grazing study used two adjacent hills, Castlelaw Hill (**Hill 1**) and Turnhouse Hill (**Hill 2**), located in South East Scotland at 55.87^{o} latitude, 3.24^{o} longitude, and 55.85^{o} latitude, 3.27^{o} longitude, respectively. Hill 1 covers an area of 287 ha and has an altitudinal range from 245 to 488 meters above sea level (**m.a.s.l.**), while Hill 2 covers an area of 187 ha and has an altitudinal range from 230 to 505 m.a.s.l. A detailed vegetation map of the study site was produced from aerial photography and ground truthing, which identified ten major plant communities. Predominant indigenous species in the vegetation were dwarf shrubs *Calluna vulgaris* and *Vaccinium myrtillus*, grasses *Nardus stricta*, *Agrostis capillaris*, *Festuca ovina*, and *Deschampsia cespitosa*, the fern *Pteridium aquilinum* and the rush *Juncus effusus*. Monthly values of dry matter digestibility (**DMD**) of these different plant species are described in Table 9.

Table 9. Dry matter digestibility of indigenous vegetation on the semi-natural hill grassland used in the present study

Species[1]	Digestibility, g.kg DM^{-1}			Author
	Jul	Aug	Sep	
Agrostis/*Festuca*	768	613	700	Armstrong et al. (1986; 1997b)[2]
Nardus stricta	634	525	453	Holland (2001)[2]
Vaccinium myrtillus	268	268	268	González-Hernández and Silva-Pando (1996)[2]
Calluna vulgaris	559	487	456	Milne (1974)[3]
Deschampsia cespitosa	449	407	226	Walsh (1995)[2]
Juncus effusus	145	128	118	Holland (2001)[2]
Pteridium aquilinum	380	380	380	González-Hernández and Silva-Pando (1996)[2]

[1]There is no information on the nutritive value of *Luzula sylvatica* and *Ulex europaeus* has no nutritive value. Only limited ground vegetation was present in the woodlands and scree. Therefore, their digestibility was assumed to be null and not considered for further calculations.
[2]*In vitro* DMD from forage cut at the ground level.
[3]*In vivo* DMD from forage cut at the ground level.

The resulting activity and GPS data points were then linked to the vegetation maps using the Geographic Information System ArcGIS 9.2 (Environmental Systems Research Institute Inc., Redland, CA). As a result, an estimation of the time that cows spent active on each vegetation type was obtained. This actual measured information was used for simulating the diet selected by cows. The time that cows spent active on each plant community was used as an equivalent surrogate measure of the proportion of species selected and present in the daily diet (Table 10). A predicted value of DMD of the selected diet was estimated for each month for each genotype for all years by multiplying the monthly digestibility value of each species with their proportion of time predicted previously. Cows spent some of their active time in habitats dominated by woodlands, scree, *Ulex europaeus*, and *Luzula sylvatica*. These areas were judged not to contribute with palatable forage for cattle feeding and therefore were not considered when estimating the total quality of the selected diet. As data of GE content of the vegetation described in Table 9 was unavailable in the literature, it was assumed that for diets with lower or higher ME content of 8 MJ/kg DM, diet had 18.1 or 18.5 MJ/kg DM of GE content, as suggested by MAFF (1990).

Physical activity in the form of distances walked in horizontal and vertical direction, were calculated from GPS data. The GPS error, whereby a stationary cow appears to move both horizontally and vertically, was reduced by using 15 min moving intervals. Then the angle was calculated for every single triangle (horizontal and vertical movement within 15 min). The dataset also included the slope of the topographic map and was linked to the locational data. The calculated average slope from the horizontal and vertical movement data and the average slope calculated from the topographic map were matched and gave an indication that the interval of 15 min was a good interval choice. All intervals were checked according to the activity type, derived from tilt sensor data, and only intervals which had a consistent animal activity period of 15 min were included in the calculations of the distances walked. The average horizontal and vertical movement (speed, km/h) and the average slope (angle, °) were calculated for each genotype. Then, the average horizontal and vertical movement walked was used in conjunction with the whole dataset of active time per day (speed × hours = distance) to compute the total distances walked vertically and horizontally.

Table 10. Proportion of active time (mean of 3 yr ± standard deviation) spent by cows of each genotype (Aberdeen Angus cross Limousin (AxL, n = 44), Charolais (CHA, n = 45) and Luing (LUI, n = 42)) on each habitat type of a semi-natural hill grassland

Habitat type	Active time, % AxL	CHA	LUI
Agrostis/Festuca	34.7 ± 9.41	43.3 ± 12.72	36.5 ± 9.50
Nardus stricta	26.3 ± 1.40	28.2 ± 7.51	26.0 ± 7.50
Vaccinium myrtillus	8.8 ± 3.07	7.5 ± 1.39	8.1 ± 2.71
Calluna vulgaris	7.6 ± 6.60	2.9 ± 1.30	8.4 ± 4.35
Deschampsia cespitosa	5.6 ± 1.78	3.1 ± 1.22	4.0 ± 1.01
Woodland	5.4 ± 3.88	5.1 ± 5.12	5.8 ± 4.66
Pteridium aquilinum	4.4 ± 3.43	3.5 ± 3.96	4.0 ± 3.14
Juncus effusus	3.9 ± 1.17	3.6 ± 1.30	4.3 ± 1.58
Ulex europaeus	2.5 ± 2.54	1.7 ± 1.62	1.5 ± 2.33
Scree	1.0 ± 0.38	0.9 ± 0.61	1.1 ± 0.45
Luzula sylvatica	0.4 ± 0.44	0.5 ± 0.57	0.5 ± 0.50

3.2.3 Energy, intake and methane estimations

Metabolic energy requirements (**ME**) of lactating cows and calves at side (cow-calf) were estimated using prediction equations in AFRC (1993). These calculations were based upon actual data on BW, BWC, pregnancy, and lactation stages, digestibility of the selected diet and physical activity as horizontal and vertical meters walked per day.

The energy required for activity was initially predicted using the energy expenditure coefficient suggested by AFRC (1993; 2.6 and 28 J·kg $BW^{-1}·m^{-1}$ horizontal and vertical, respectively). As different values for energy expenditure of grazing animals on the hill ground are available in the literature (Brosh et al., 2010; 0.62 and 5.17 J·kg $BW^{-1}·m^{-1}$ horizontal and vertical, respectively), a sensitivity analysis was performed of the use of more suitable coefficients of energy allowance.

The ME for lactation was estimated to be proportional to the amount of milk the calves were estimated to consume. This was predicted from the total ME requirements of the calf depending on its actual BW and BWC, and assumptions about the share of energy intake by the calf between milk and grass. Further, a maximum milk production potential was determined by the equation: milk yield (kg/d) = 8.0 * $n^{0.121}$ * $e^{-0.0048*n}$; where n denotes week of lactation (AFRC, 1993) and lactation was limited by this amount. The cow-calves on the experiment were towards the end of their lactation (weeks 16 to 24) and at this stage it is generally known that calves are able to graze and ruminate. For instance, Le Du (1976) reported values of grass intake between 0.7 to 3 kg OM/head of calves. However, little information is available in the literature regarding milk:grass ratio of calves grazing extensive hill vegetation and in the present study this ratio was unknown. It was therefore assumed that the milk intake represented 50, 40, and 30% of the calves' diet in July, August and September, respectively. These proportions were selected as they were in agreement with the amount of milk production of beef cows of similar genotypes and stage of lactation (Funston et al., 1991; Wright et al., 1994; Sinclair et al., 1998a). Under these assumptions, the estimated milk consumed by calves was always below the potential milk production of cows. Later, given the potential uncertainty of CH_4 outputs due to these assumptions, a sensitivity analysis of milk:grass ratio was also undertaken.

Based on the predicted energy content of the complete diet, weighted by differing amounts of hill grasses and differing DMD, DMI was then estimated as the amount of feed each cow and calf needed to cover their energy requirements (AFRC, 1993). As this DMD adds potential error and uncertainty, a sensitivity analysis of this factor was carried out.

The potential CH_4 emission was predicted by an equation for beef cattle based upon this DMI value as: CH_4 (g/d) = (35.1 * DMI (kg/d) + 14.7)*1000 / 1400, modified from Yan et al. (2009). This equation was selected as it was developed from beef cows and it is sensitive to changes of measured performance. Methane outputs ($g \cdot cow^{-1} \cdot d^{-1}$; $g \cdot calf^{-1} \cdot d^{-1}$; $g \cdot$cow-calf $pair^{-1} \cdot d^{-1}$) and CH_4 yield (pair CH_4 100 MJ/MJ GE intake (**GEI**)) were estimated.

Means and deviations of observed individual performance were used for studying the potential effect of measured activity on CH_4 emissions at the herd level. Methane emissions per kilogram of production (CH_4, kg/kg production) during July, August and September (92 d) were estimated from a simple simulated breeding herd of 100 cows and divided by the kilograms of calf BW produced in that period (calf BW minus calf birth BW). The CH_4 of the system was then estimated as: cow-calf pair CH_4 * 100 (herd) * 92 (d) / ((calf BW – calf birth BW) * 80 (sellable calves)). Due to the uncertainty of the impact of reproductive efficiency on the final herd results, another sensitivity analysis was performed on this factor.

The cumulative effect of actual performance, diet selection, and physical activity on potential CH_4 output and yield was estimated in 5 incremental calculation tiers (Table 11), considering:

1) Actual variable BW but with identical performance (maintenance level only), an average DMD of the grazed vegetation (0.567 kg/kg DM in average) and a standard activity as recommended by AFRC (1993) for beef cows (0.0071 $MJ \cdot kg\ BW^{-1} \cdot d^{-1}$);

2) As 1) but with actual individual performance data, considering cows and calves BWC, lactation and pregnancy (Table 12, Figure 6);

3) As 2) but using actual activity patterns (horizontal and vertical distances walked per day, Table 12) and again with average diet DMD;

4) As 2) but with different diet DMD predicted by actual data on foraging behaviour of cattle on different habitats and, as in 1) and 2), with standard activity;

5) All the actual effects from preceding tiers combined.

Table 11. Calculation tiers used to model levels of performance and predict DMI, energy requirements and methane outputs

Tier	Performance	Activity	Diet	Actual values used
1	maintenance	standard	standard	BW
2	actual	standard	standard	BW + Performance
3	actual	actual	standard	BW + Performance + Activity
4	actual	standard	actual	BW + Performance + Diet
5	actual	actual	actual	BW + Performance + Activity + Diet

3.2.4 Experimental design and statistical analysis

Two fenced grazing areas (Hill 1 and 2) with different proportions of the main vegetation types were used during the grazing study. In year 1 (2007), 15 cows and calves of each genotype grazed together for the first time on Hill 1 for 4 wk (from July 3rd to August 8th) and then on Hill 2 for another 4 wk (from August 21st to September 20th). In the subsequent 3 yr of the study (2008 to 2010), 2 genotypes were used each year for 8 weeks, alternating genotype combinations subsequently (CHA and LUI from July 7th to September 10th, 2008; AxL and LUI from July 2nd to September 10th, 2009; and AxL and CHA from July 5th to September 10th, 2010). As a result, 3 repetitions from each genotype were obtained over the 4 yr of the study. Some animals were replaced during the experiment. Thus, a total of 44, 45, and 42 observations of performance were obtained for AxL, CHA and LUI, respectively.

The DMD of selected diets was compared between genotypes using year, month and grazing area (Hill 1 or 2) as covariates. Although in the current study average values of activity and diet selection for each genotype by month by year combination were used, individual observed data of animals BW and BWC were available and used to represent variability and to compare results between genotypes. Within and between calculation tiers, genotypes were compared for their energy requirements, DMI and CH_4 emissions. The CH_4 output of the simulated herds were compared across genotypes, using 3 repetitions (years) per genotype.

Results were analysed in a completely randomized design with genotypes or calculation tiers when appropriate as factors, using the GLM procedure of SAS (SAS Inst. Inc., Cary, NC). Pre-planned contrasts were used to calculate differences between genotypes and calculation tiers. The MEANS procedure was used to calculate means and standard errors.

3.2.5 Sensitivity analyses

Assumptions were made in this study to complete the dataset available from long-term experimental data. Assumptions affecting predicted energy requirements (such as energy cost of activity and milk consumed by calves), values of DMD of intake and reproductive efficiency of cows are all likely to have a major and direct impact on the predicted values of CH_4 emissions and outputs from these type of systems (Reynolds et al., 2010). Thus, sensitivity analyses were performed for each of these 4 factors to understand the scale of the impact of using different assumptions and likely error or uncertainty of using particular assumptions.

Calculations of the energy cost of activity were made considering the coefficients for energy expenditure suggested by either AFRC (1993) or Brosh et al. (2010a). They were applied to actual observed data of horizontal and vertical distances walked to study the impact on the final results of the system of a bias in these coefficients.

The amount of milk consumed by calves represents an important part of both cow and calf energy requirements, having a direct effect on the final CH_4 results. Thus, to illustrate the effect of a different milk:grass ratio of the calves' diet on CH_4 estimation, 5 levels of milk consumption of 100, 75, 50, 25, and 0% for each of the 3 months were used for simulation.

Values of DMD used in this study were obtained from the literature and were not measured on site; such *in situ* measurement of DMD intake of free ranging cattle grazing in complex habitats without potentially modifying behaviour is difficult to obtain. Thus, a range of levels of DMD values (49, 50, 51, 52, 53, 54, 55, 60, and 65%) for each of the 3 months was used to simulate both the effect of cattle selecting different qualities of pasture intake, and of using literature data for rangeland systems which have highly variable temporal and spatial distribution of vegetation quality.

To understand how scaling up from a relatively controlled and short time scale of measurement to the issues that affect annualized farm systems, a fourth sensitivity analysis was performed. This assessed the potential effects of different reproductive efficiencies among genotypes on the overall CH_4 emissions at the cow-calf system level. A range from 60 to 100% of weaning rates were then applied to the herds to illustrate the impact of this efficiency factor that is likely to vary between farming systems and between breeds.

3.3 Results and discussion

3.3.1 Activity

The total active time recorded on the database averaged 9.2 ± 0.27, 9.8 ± 0.48 and 10.2 ± 0.44 $h \cdot cow^{-1} \cdot d^{-1}$ for AxL, CHA and LUI, respectively. On average, over the whole experiment CHA cows tended to walk more horizontal and vertical distances than AxL and LUI (Table 12). Results found in the literature are inconsistent regarding breed differences on activity patterns. With lactating beef cows of 6 to 9 yr old, Funston et al. (1991) observed that Simmental x Hereford cows tended to walk longer distances than pure Hereford and its crosses with Aberdeen Angus; even though no differences in BW were reported. In a different trial of the same study, although prior differences on BW were observed, no differences on distances walked were found among other breed types of younger cows (3 years old). On the contrary, Hessle et al. (2008) found that heifers of a traditional Swedish breed Väneko (small frame) were more active than the larger CHA when grazing heterogeneous semi-natural grasslands. In the present study, comparing data from 6 to 7 years old cows, CHA (heavier breed) tended to be more active than smaller frame genotypes (a traditional breed). Results from the present study differed from those reported by Hessle et al. (2008) probably as they used a smaller grazing area (2.2 to 4.1 ha), younger cattle (8 mo old), and more homogeneous vegetation than those used in the present study. Cows of heavier genotypes typically consume more energy in order to perform well. Moreover, in the present study cows grazed the heterogeneous vegetation for the first time without adaptation to the new environment. This was explicitly done in order to study the effect of genotype of cows on their grazing behaviour in these new conditions for all of the cows under study. This lack of adaptation together with the higher energy requirement can explain that Charolais cows walked longer distances in order to find better quality grass.

Minimum and maximum distances walked observed in the present study for all genotypes were 3.0 to 6.0 and 0.5 to 0.8 $km \cdot cow^{-1} \cdot d^{-1}$ in horizontal and vertical direction, respectively. These ranges were greater than those reported previously from foothill grazing cows with maximum of 3.6 and 0.12 km/d horizontally and vertically, respectively (Brosh et al., 2010a). In that study, cows were allocated to paddocks of 107 ha with a stocking rate of 0.48 cows/ha on average. The paddocks used to collect the dataset of the present study were larger and with about half the stocking rate of Brosh et al. (2010), which could explain the greater distances observed.

Table 12. Means ± standard errors of actual distances walked, BW, BW change and predicted dry matter digestibility of the diet, intake and methane outputs from Aberdeen Angus cross Limousin (AxL, n = 44), Charolais (CHA, n = 45) and Luing (LUI, n = 42) pregnant

	AxL	CHA	LUI	P-value[7]
Activity[1], m/d				
Horizontal	4528.9 ± 331.00	4718.0 ± 290.44	3881.4 ± 309.27	-
Vertical	619.9 ± 20.20	636.1 ± 31.91	566.1 ± 34.14	-
BW, kg				
Cows	711.9 ± 4.90^{b}	785.1 ± 5.46^{a}	622.3 ± 5.14^{c}	< 0.0001
Calves	183.3 ± 3.44^{a}	181.2 ± 3.60^{a}	168.0 ± 3.84^{b}	< 0.0001
BW change[2], g/d				
Cow BWC[2]	-166.8 ± 29.40^{b}	-143.9 ± 50.54^{b}	63.7 ± 22.49^{a}	< 0.0001
Calf BWC	976.6 ± 19.09^{b}	1000.0 ± 13.03^{ab}	1042.7 ± 14.97^{a}	< 0.0001
Digestibility				
DMD[3], g/kg DM	530 ± 18.2^{b}	560 ± 19.6^{a}	536 ± 16.9^{ab}	0.002
Intake				
Cow DMI, kg/d	17.9 ± 0.24^{a}	17.2 ± 0.24^{b}	16.6 ± 0.22^{b}	0.0006
Cow GEI[4], MJ/d	326.9 ± 4.19^{a}	313.3 ± 4.33^{b}	305.2 ± 3.82^{b}	0.0011
Methane[5]				
CH_4, g·cow^{-1}·d^{-1}	460.4 ± 6.00^{a}	441.6 ± 6.03^{b}	427.7 ± 5.61^{b}	0.0006
CH_4, g·calf^{-1}·d^{-1}	130.6 ± 4.22^{a}	112.4 ± 3.35^{b}	138.7 ± 4.79^{a}	< 0.0001
CH_4, g·pair^{-1}·d^{-1}	591.0 ± 9.47^{a}	554.0 ± 8.55^{b}	566.4 ± 9.66^{ab}	0.0153
CH_4, %GEI pair/d	7.90 ± 0.004^{a}	7.94 ± 0.021^{a}	7.85 ± 0.013^{b}	< 0.0001
CH_4[6], kg/kg production	0.49 ± 0.024^{a}	0.48 ± 0.029^{a}	0.50 ± 0.042^{a}	0.909

[a-c] Within a row, means without a common superscript differ (P< 0.05). [1]Mean daily distances walked using data from GPS collars. [2]BWC = BW change. [3]DMD = DM digestibility. [4]GEI = GE intake. [5]Predicted with the equation CH_4 (g/d) = (35.1 * DMI (kg/d) + 14.7)*1000 / 1400; modified from Yan et al. (2009). [6]Kilograms of CH_4 produced by the cow-calf pair during the 3 months of experiment per kilogram of BW produced on farm assuming 20% of replacement rate, calculated as: cow-calf pair CH_4 * 100 (herd) * 92 (d) / ((calf BW – calf birth BW) * 80 (sellable calves)). [7]*P*-values for the effect of genotype.

3.3.2 Energy requirements

It is not the main objective of this paper to conclude whether one genotype is better than another, but to describe how their differing foraging activity can potentially affect the final energy balance, and resulting methane output, of the cow-calf system. Thus, to understand the origin of these differences, a synthesis of how different genotypes used the available energy is described.

As expected, there was a significant effect of genotype on the energy required for maintenance ($P < 0.0001$) and production ($P < 0.0001$; Figure 6), reflecting measured performance data. A significant contribution ($P < 0.0001$) of energy expenditure for physical activity to the total ME required was also observed. Combining the observed distances walked with the coefficients of energy allowance suggested by AFRC (1993), they represented 27, 29 and 23% of the total ME for AxL, CHA and LUI, respectively ($P < 0.0001$; Table 12). It is assumed by AFRC (1993) that 2.6 J/kg BW are needed for every meter walked horizontally and a 10 fold of this amount is required for every meter walked in a vertical direction. These coefficients for energy expenditure have been obtained in unnatural conditions, such as cows walking on treadmills with varying slopes. Lower coefficients were reported at similar levels of gradient of 6% (di Marco and Aello, 1998). With higher slopes of up to 20% Brosh et al. (2010a) observed energy expenditure coefficients of 0.62 and 5.17 $J \cdot kg\ BW^{-1} \cdot m^{-1}$ for horizontal and vertical meters walked, respectively. The dataset used in the present study was generated from cows grazing slopes of 11 to 15% on average for the 3 genotypes (Umstätter et al., 2009). These conditions are comparable with Brosh et al. (2010a) and later a sensitivity analysis was performed to illustrate the potential impact of applying coefficients mentioned by Brosh et al. (2010a) instead of the AFRC (1993) model.

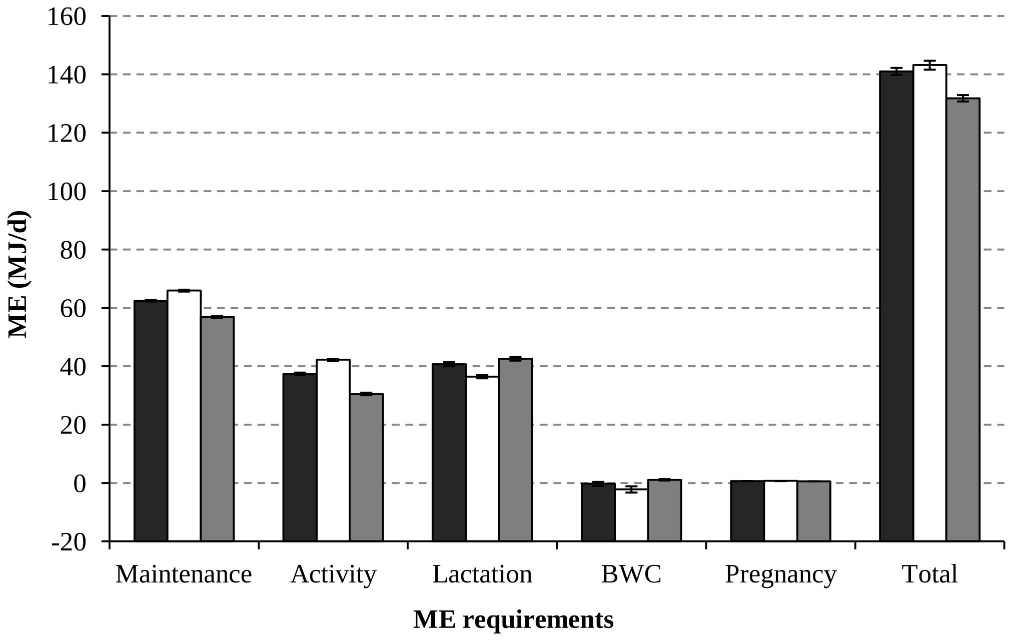


Figure 6. Mean ± standard error (error bars) of energy requirements for maintenance, activity, lactation, BW change (BWC) and pregnancy estimated using AFRC (1993) for Aberdeen Angus cross Limousin (n = 44; black bars), Charolais (n = 45; white bars) and Luing (n = 42; grey bars) cows

3.3.3 Diet selection and intake

Values of digestibility used in the present study were assumed from the literature, in which samples were obtained by cutting the grass at the ground level. These values would underestimate the actual DMD of the forage selected by animals, as the herbage at ground level have lower digestibility compared with the leaves and soft stems selected during grazing. Thus, results from this study might be drawn with care as no actual measurement of the herbage selected by cows was available at the location of the study. Although the measures of DMD may not represent what the animals have selected to eat, they indicate that there is variation on the quality of the forages between different plant communities. Sensitivity analyses of variation in digestibility were also conducted to enable understanding of the uncertainty created by lack of information in both this study, but also in practice, of the actual intake and digestibility of cattle on heterogeneous pastures.

The estimated DMD of selected diets was significantly different for grazing area (*P* < 0.014), month (*P* < 0.0001) and genotype (*P* = 0.002); without differences between years (*P* = 0.373). No significant effect was observed for the interaction between genotype and month or grazing area (*P* > 0.25). The resulting DMD of the diet selected by CHA was significantly greater than AxL and LUI (*P* = 0.001 and 0.002, respectively), without differences between the last two (*P* = 0.754, Table 12).

For simulation purposes, using the proportion of time spent on a particular community of plants to estimate its importance on a daily basis was considered the most appropriate approach to estimate monthly quality of the selected diet given the type of data available. This is in agreement with observed foraging selection in similar types of grassland, where the distribution of the grazing time was better explained by matching selectivity with digestibility of the selected patches (Wallis de Vries and Daleboudt, 1994). A model to estimate DMI from these types of hill grasslands has been developed for sheep (Armstrong et al., 1997a). The use of a larger BW as input data to simulate a cow with this sheep model was decided against, due to the diverse grazing behaviour of these two species in terms of decision making and plant selectivity on a heterogeneous grassland (Grant et al., 1985). The method to describe patch selectivity assumed in the present study can be debatable, as other elements may be influencing the decision made for a particular location selected for grazing, such as the proximity to a water source, the presence of obstacles or even the presence of other animals associated with social behaviour. However, as far as I am aware, this is the first attempt to combine GPS and activity sensor data with GIS maps for simulation purposes providing with valuable information for understanding the level of impact of the grazing behaviour on CH_4 prediction, and further direct measurements are needed to validate the results obtained.

The CHA cows tended to have a greater DMI than LUI (*P* = 0.097), but there were no differences on GEI between these two genotypes (*P* = 0.168, Table 12). The AxL cows required more energy than LUI but with a similar diet DMD, hence DMI was greater for AxL (*P* = 0.0001). On the other hand, AxL and CHA required a similar amount of energy, but CHA selected a significantly better quality diet and therefore

AxL required to consume significantly more than CHA cows (P = 0.024). Little information is available regarding intakes of lactating beef cows on indigenous grasslands. Studying intake related variables, Funston et al. (1991) observed that breeds of greater milk yield (Tarentaise x Simmental x Hereford) tended to have greater bite rate than pure Hereford, with no differences on grazing time and distances travelled on foothill grasslands. This supports the theory that breeds adapted to unfavourable conditions (i.e. Tarentaise vs. Hereford) have the ability to modify their grazing behaviour to meet their requirements in these conditions.

Estimated DMI values in the present study were higher than expected for similar animal categories (Barlow et al., 1988). This is also indicating that values of digestibility may have been lower than the quality of the actual intake selected by cows. This indicates that absolute values observed from this study should be used with care. The observed results still indicate that there are limitations in current modelling studies to estimate carbon budgets accurately from extensive beef production systems.

3.3.4 Methane estimation

Differences in cow-calf pair predicted CH_4 (**CH_4pair**, g·pair^{-1}·d^{-1}) were observed between genotypes (Table 12). The CH_4pair from AxL was significantly greater than CHA (P = 0.004) and tended to be greater than LUI (P = 0.063), with not differences between CHA and LUI (P = 0.342). Calves significantly influenced the total emissions of the cow-calf pair. Based upon ratios of grass:milk consumption assumed for the main calculations, their contribution to the cow-calf pair emissions were 22, 20 and 24% for AxL, CHA and LUI, respectively (Table 12).

Although differences were small, the energy lost as CH_4 from the cow-calf pair (% GEI·pair^{-1}·d^{-1}) was significantly lower for LUI (P = 0.011) and greater for CHA (P < 0.0001; Table 12), indicating that LUI cow-calf pairs made a 0.05% and 0.09% more efficient use of the energy compared with the AxL and CHA, respectively. At 100% weaning rate, the CH_4 yield of the simulated system (CH_4pair kg/kg of calf BW produced) was not affected by genotype (P = 0.909; Table 12). Nevertheless, there are typically differences in reproductive efficiency among genotypes and the impact of this factor was studied later in a sensitivity analysis.

The literature is not yet consistent on the effect of genotype on CH_4 emissions under highly controlled conditions such as respiration chambers. Previous studies did not find differences in CH_4 (L/d) comparing Holstein vs. CHA x Simmental yearling heifers (Boadi and Wittenberg, 2002), while others comparing more divergent breeds did mention differences in CH_4 (g/d) from Holstein vs. a Brazilian crossbred (Pedreira et al., 2009). Nevertheless, there is no information about CH_4 emissions from mature beef cows of different breeds grazing semi-natural grassland and therefore conclusions about breeds from this modelling study must be drawn with caution.

3.3.5 Contribution of actual performance, activity and diet quality

Differences observed between genotypes were non-constant among calculation tiers (Table 11, Figure 7). Based on tier 1 calculations, CH_4pair was 318, 324 and 311 g/d for AxL, CHA and LUI, respectively. The CH_4pair was significantly different between genotypes (P = 0.013, Figure 7), mainly due to differences observed on CH_4calf, being greater for LUI, then AxL and lastly CHA (P < 0.0001), affecting the CH_4pair emissions with the same trend.

Estimated CH_4pair on tier 2 increased significantly (P < 0.0001) to 426, 416 and 433 g/d (34, 29 and 39% of tier 1) for AxL, CHA and LUI, respectively (Figure 7). It can be observed that the order of CH_4pair among genotypes has changed, and now CH_4pair was greater for LUI due to their better performance, and thus predicted greater DMI, compared with the other 2 genotypes.

The CH_4pair increased significantly (P < 0.0001) from tier 2 to tier 3, after taking into account the actual measured physical activity over the recommended standard level by AFRC (1993). This proportion of increment was significantly different for all genotypes (P = 0.004), being 25, 29 and 19% greater than tier 2, for AxL, CHA and LUI, respectively (Figure 7). Thus, the tendency observed on measured physical activity to differ between genotypes became significant in terms of energy requirements, further affecting the total CH_4 emissions of the system.

Considering the calculated diet quality selected by each genotype (tier 4), the CH_4pair increased significantly by 12, 3 and 11% of the CH_4pair in tier 2, for AxL, CHA and LUI, respectively ($P < 0.0001$) over those estimated with a similar diet for all of them (Figure 7). The fact that CHA selected a better quality diet (i.e. more similar to the assumed average DMD used in tiers 1 to 3 than the other breeds) determined that their differences between tier 2 and 4 were smaller than the other genotypes.

Compared with previous calculation tiers, including actual activity (tier 5) CH_4pair was 24, 29 and 17% higher than tier 4 for AxL, CHA and LUI, respectively but still lowest per cow-calf pair for CHA than the other 2 genotypes (Table 12).

This modelling exercise illustrated the importance of considering the potential diet selection that these genotypes may have as a result of diverse measured activity patterns. This also demonstrates that special care is needed for future carbon inventories for predicting CH_4 production of ruminants grazing heterogeneous vegetation. Although *in vitro* digestibility of the available grassland may be measured, this still does not reflect the differing selection processes of diverse cattle breeds, and thus scope for considerable variation in true *in vivo* digestibility.

These tier comparisons help to understand the relative importance of considering either actual activity patterns or actual estimates of diet selectivity on the final results. Different responses can be observed among genotypes when comparing calculation tiers. Physical activity was a major contributor to determine the trend of the results observed in tier 5, when all the actual factors are taken into account (Figure 7, Table 12).

Lassey (2008) discussed uncertainty associated with 'bottom-up' estimates of CH_4 based upon controlled experiment was ± 21%. Although this author mentioned grazing selectivity to include uncertainty to CH_4 estimates, he did not mention grazing activity as an issue for CH_4 predicted from extensively-managed livestock.

Thus, the present study provides clear evidence of the importance of differentiating the grazing behaviour that the 3 genotypes are expressing, affecting not only the energy required for different physiological functions and performance but also their carbon budget through quality of the selected diet, their activity and final amount of feed consumed.

Methane emissions are only one part of overall carbon budgets and the environmental impact of cattle grazing systems. There are likely to be other impacts on faecal and urinary outputs of cattle and upon resulting fluxes of the combination of these outputs and their location, together with grazing impacts, upon a range of carbon fluxes of the rangeland vegetation and soils (Derner and Schuman, 2007). Moreover, distinctive selection “pressure” of cattle breeds could have a long term impact on biodiversity associated with sensitive semi-natural vegetation by varying their active time (grazing, trampling, faecal and urinary deposition) on different vegetation species and disturbing the condition and balance of species of these types of habitats.

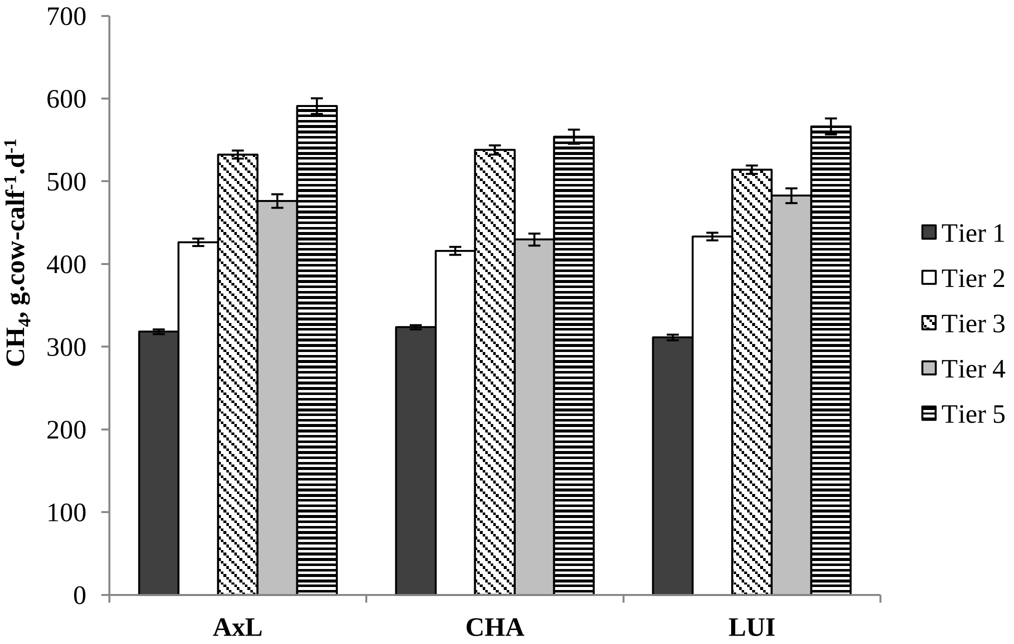


Figure 7. Mean cow-calf pair methane (CH_4) of Aberdeen Angus cross Limousin (AxL, n = 44), Charolais (CHA, n = 45) and Luing (LUI, n = 42) pairs estimated with the 5 calculation tiers considering: 1) maintenance level, standard diet and activity, and actual BW; 2) standard diet and activity and actual BW and performance; 3) standard diet and BW, performance and activity; 4) standard activity and actual BW, performance and diet; and 5) actual BW, performance, diet and activity

3.3.6 Sensitivity Analyses

3.3.6.1 Energy cost of activity

Using the conversion factors of activity into energy suggested by Brosh et al. (2010a), CH_4 was 83 g·cow^{-1}·d^{-1} and 91 g·pair^{-1}·d^{-1} (19 and 16%) lower than applying the AFRC (1993) suggested coefficients (P < 0.0001). This variation in the results due to the use of diverse conversion factors can lead to strongly biased carbon budgets, raising the question of which of these coefficients is more suitable to use. There are enormous differences between the studies reported here. While AFRC (1993) assumed coefficients obtained by Ribeiro et al. (1977) with animals walking on treadmills with zero and 6 degrees of gradient, Brosh et al. (2010a) utilized an alternative method to predict energy expenditure *in situ* from animals grazing on the hill ground and expressing their natural behaviour. Both studies provide estimates of the energy cost of activity, hence it is a matter of deciding if observations from animals that are able to express their natural behaviour are more reliable than those from unnatural but controlled conditions.

The IPCC (2006) Tier 2 methodology for predicting energy requirements of cattle considers the cost of activity as an increment of 17% on the energy requirements for maintenance of animals grazing in small areas with high grass availability and a 36% increment for those grazing open range areas where activity constitutes a significant cost. In the present study, based on AFRC (1993) coefficients, the energy cost of activity was 60, 64 and 54% of those for maintenance, whereas based upon the Brosh et al. (2010a) coefficients they represented 20, 21 and 19% for AxL, CHA and LUI, respectively. These large differences among studies reflect the different methodology used to determine the energy cost of activity. More energy expenditure is estimated using coefficients form AFRC (1993) than Brosh et al. (2010a). Higher estimates could reflect the fact that animals used in studies used by AFRC (1993) were forced to exercise for a given period of time that differed with their natural pattern of activity. It could also be explained as the energy provided by standard diets used under controlled experiments differed from what the animals would have been able to select in outdoor grazing conditions for the same level of activity. All this suggest that values of energy cost of activity reported by Brosh et al. (2010a) are more suitable to be applied to obtain estimates of energy expenditure from grazing animals.

It is difficult to find a clear explanation in the literature of how the energy allowance for activity is estimated in other studies using simulation models and system analysis. Indeed in many studies it is unclear whether it is accounted for or not. Again, this study illustrates the magnitude of bias that can be expected depending on the methodology used and assumptions made regarding this factor. More accurate and precise estimations of the energy cost of activity and animals' activity in free-range conditions are crucial to reduce the uncertainty on the estimations of environmental impact of these types of production systems.

3.3.6.2 Diet digestibility

As described above, using estimated DMD based upon measured different foraging patterns, CH_4pair was greater for AxL, followed by LUI and CHA (Table 12). Simulating equal DMD levels (assuming no diet selection took place), CH_4pair from CHA would be similar to AxL ($P > 0.50$) and both greater than LUI ($P = 0.011$ and 0.042, respectively). The sensitivity analysis demonstrated that if the DMD of CHA intake is 20 g/kg DM greater than AxL (an increment of 4% of DMD, only 0.3 MJ of ME greater) CHA will produce less CH_4pair emissions than the other 2 genotypes ($P < 0.004$). Further simulations demonstrated that CHA and AxL would have to increase their DMD by 20 and 30 g/kg DM (4 and 6% increment, 0.3 and 0.5 MJ more; respectively) to have lower CH_4pair emissions than LUI ($P = 0.0004$ and 0.031, respectively; Figure 8).

Considering the large variation of the quality of the vegetation over the year and between years results from this modelling study suggest that the observed trends among genotypes of different foraging behaviour and selectivity should be taken into account for future CH_4 estimations of free-range cattle grazing in extensive conditions, and identified in uncertainty analysis for producing farm, national of global inventories of CH_4 emissions. These results are in agreement with the theory that animals are able to change their behaviour to optimize their foraging activity and intake (Wallis de Vries and Daleboudt, 1994). Some animals spend more energy on getting better food; others use less energy by accepting poorer food. It was further observed in the present study that this spontaneous behaviour differed among genotypes and had a significant impact on predicted CH_4 emissions. Thus, cows produce less CH_4 by eating better food, but produce more CH_4 by needing more energy to walk further to find it.

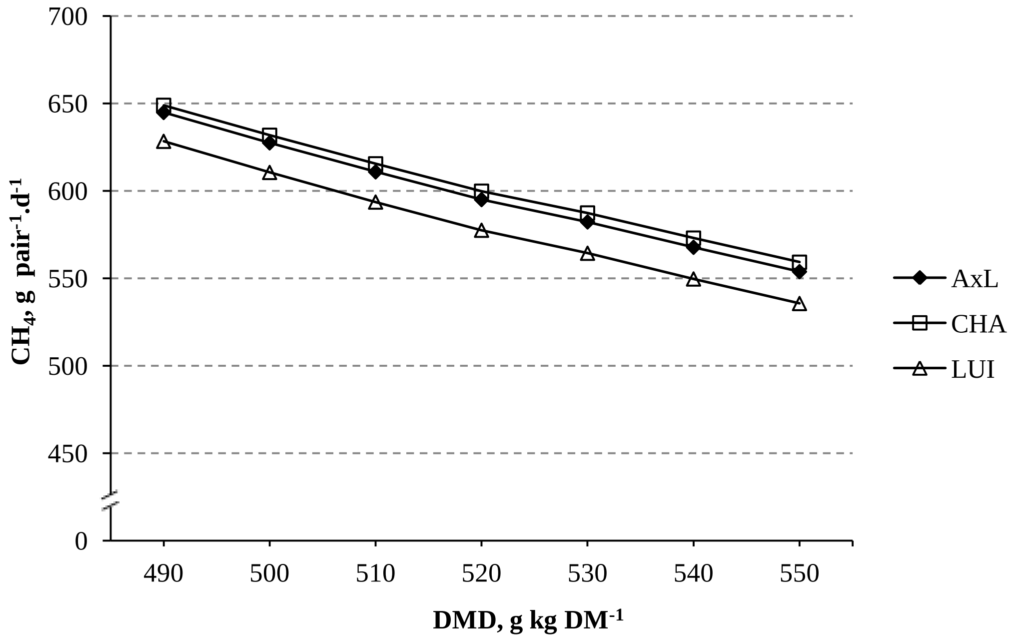


Figure 8. Mean methane (CH_4) from cow-calf pairs of Aberdeen Angus cross Limousin (AxL, n = 44), Charolais (CHA, n = 45) and Luing (LUI, n = 42) genotypes, estimated for a diet of varying dry matter digestibility (DMD)

3.3.6.3 Milk production

After maintenance, milk production is the most energy demanding function of the cow and changes in this flux will affect energy intake and losses. Compared with a calf whose diet consists of 100% milk, reducing it to 75, 50, 25 and 0% of milk in calves' diet will reduce cow CH_4 in average for the 3 genotypes by 1, 15, 82 and 166 g/d, respectively (Figure 9). However at the same time, replacing milk by grass in the calves' diet will increase their CH_4 production. Increments of 1, 9, 46 and 93 g/d were observed in calves' CH_4 production by changing the milk proportion at the above mentioned levels, respectively (Figure 9). As reducing the milk proportion of the calf's diet has a major impact on the cow rather than the calf, the overall cow-calf pair CH_4 was reduced by 0, 7, 36 and 73 g/d if the proportion of milk in calf's diet is 75, 50, 25 and 0%, compared with 100% milk, respectively. The sensitivity analysis showed that changing the previous assumptions towards 100, 75, 50 or 25% will only affect cow-calf pair CH_4 emissions by ± 3%. Thus, it can be concluded that the assumptions made for calculations, which were based upon previous studies of milk production, provided solid information and little variation on the final results are likely to occur by any biased assumptions.

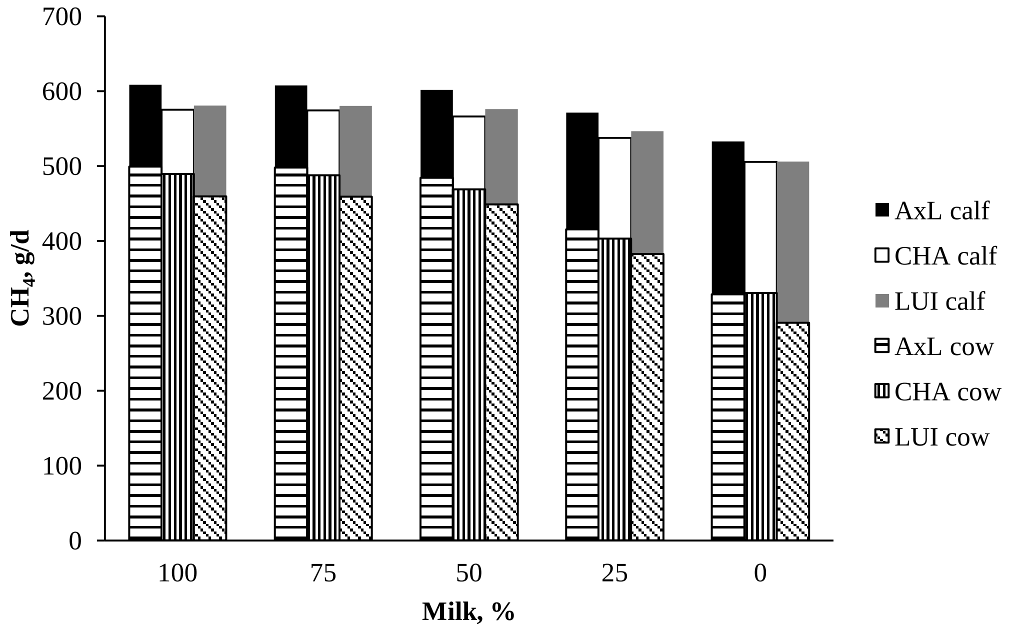


Figure 9. Mean methane (CH_4) produced by cows (pattern fill) and calves (solid fill) of Aberdeen Angus cross Limousin (AxL, n = 44), Charolais (CHA, n = 45) and Luing (LUI, n = 42) genotypes, estimated for decreasing proportion of milk in calves diet.

3.3.6.4 Reproductive efficiency

Although there were no differences in predicted CH_4 outputs of the system (kg CH_4/kg production) between genotypes (Table 12), these results assumed 100% production efficiency as it used an experimental study with all cows rearing calves. This is certainly not the case in reality at the farm system level. Genotypes are often reported to differ in their reproductive efficiency, with different responses under different types of production system. For instance, it has been reported that CHA cows under unfavourable conditions have poor reproductive rates (Sinclair et al., 1998b). This index is an example of a major measure of efficiency that should be considered when drawing conclusions about management options at the system level.

Although not significant, with the same reproductive efficiency, CHA had lower CH_4 per kg of production than AxL and LUI (Table 12). In this study, the sensitivity analysis demonstrated that a decrease of 3 and 4% in weaning rate of CHA can cancel out this difference observed with AxL and LUI, respectively (Figure 10).

Historical data of conception rates collected in the last 4 years (2009-2012) at the SRUC Beef Research Centre (Easter Howgate, Edinburgh, UK), showed the AxL cows as the most reproductive efficient genotype, followed by LUI and CHA (80, 75 and 65% conception). With a 65% weaning rate, CHA herds will produce 101 g CH_4/kg production (17%) more above that expected from AxL at 80% weaning rate and 60 g CH_4/kg production (10%) more than LUI at 75% weaning rate. Weaning rates for CHA have been mentioned to be 60.9% (Lamb et al., 1992). Other authors have published conception rates below this value (Sinclair et al., 1998b; Muller et al., 2010; Pellegrini and Lopes, 2011; Vaz et al., 2012), meaning that weaning rates can be even lower than 60% for this genotype. For AxL weaning rates were described to be 80.6% (Lamb et al., 1992) and 96% for LUI cows (Scheider and Distl, 1994). Under similar conditions as evaluated in the present study where cows cannot reach their energy requirements and lose weight, reproductive performances may be compromised and differences among genotype performance could become even larger.

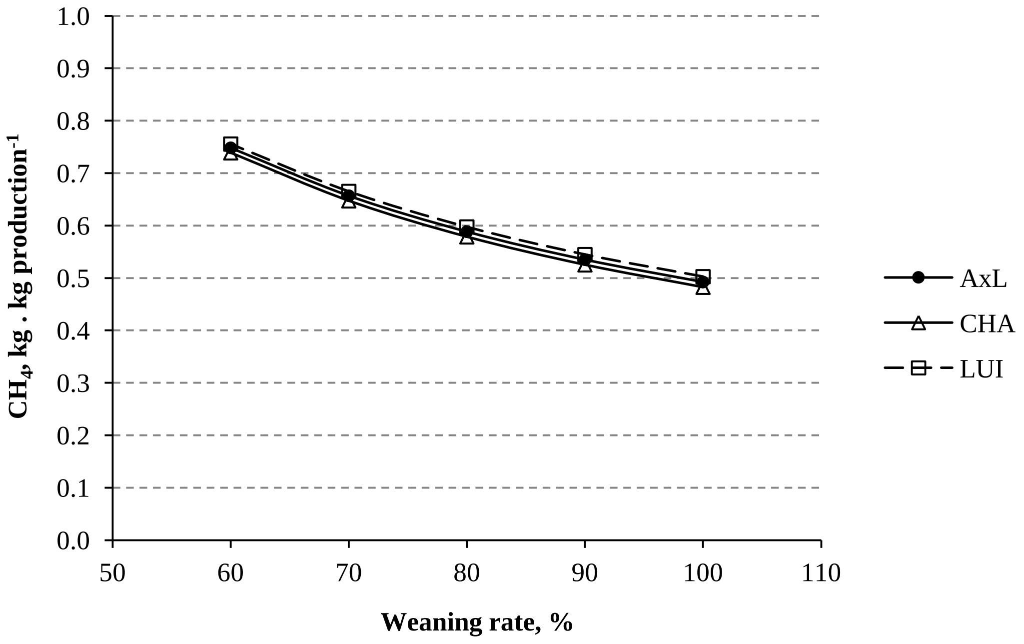


Figure 10. Mean cow-calf pair methane (CH_4) emissions per kilogram of calf BW produced on farm during experimental period predicted as: cow-calf pair CH_4 * 100 (herd) * 92 (d) / ((calf BW – calf birth BW) * 80 (sellable calves)), from Aberdeen Angus cross Limousin (AxL, n = 44), Charolais (CHA, n = 45) and Luing (LUI, n = 42) simulated herds with declining weaning rates

3.4 Conclusion

By introducing measured performance and activity data into a modelling study, this study has demonstrated for the first time that differences in energy requirements driven by diverse physical activity have a potential impact on predicted CH_4 emissions of extensively-managed cow-calf systems. Further, the study shows how different genotypes may deal with these differences through adapting their foraging behaviour, diet selection and activity patterns. Observed patterns of activity contributed significantly to determining the trend of the results observed in CH_4 emissions among genotypes. The use of coefficients to convert activity into energy more appropriate for the type of landscape and extensive management are crucial. A gap in the knowledge of the relationship between energy expenditure of animals grazing across a range of slopes was identified, which could help to explain large differences observed in the literature. Methane estimations were highly sensitive to changes in quality of the diet, highlighting the importance of considering animal selectivity on heterogeneous grasslands in future carbon budgeting. At the farm-system level, this study demonstrates that differences in CH_4 outputs in response to diverse grazing behaviour can be as important as varying reproductive efficiency. Information about CH_4 emissions from beef cows grazing rangelands is scarce and extrapolations from housed or grazing studies under dissimilar conditions are of risk of under-estimating the uncertainty of the predictions. This modelling exercise further helps to illustrate the need to assess grazing adaptability of some genotypes to more challenging environments to improve the efficiency of cattle breeding on heterogeneous grasslands, both in terms of environmental impact and food supply.

3.5 Annexed results

Additional results not included in the article submitted for publication are presented here. Work for Chapters 2 and 3 was performed simultaneously, the CH_4 predictions mentioned in this Chapter were obtained by using an equation mentioned in the literature (Yan et al., 2009) instead of the new set of equations developed in Chapter 2. Thus, the aim of this annexed section is to provide the main results using the same set of data to demonstrate how the results shown in Chapter 3 would change by using prediction equations developed in Chapter 2.

Therefore, 2 questions arise. Firstly how comparable are NewEqGEI from Chapter 2 and the equation from Yan et al. (2009) used in this Chapter, and secondly how the results of Chapter 3 would have differed if NewEqGEI have been used instead.

To answer the first question, the equation from Yan et al. (2009) was used to predict CH_4 from the validation dataset utilized in Chapter 2 in order to assess its ability to predict observed CH_4 emissions. Results demonstrated that predictions obtained with the equation from the literature (Yan et al., 2009) had a good relationship with observed CH_4 values (R^2 = 0.69), however this equation tend to overestimate the observed values in the dataset (Figure 11).

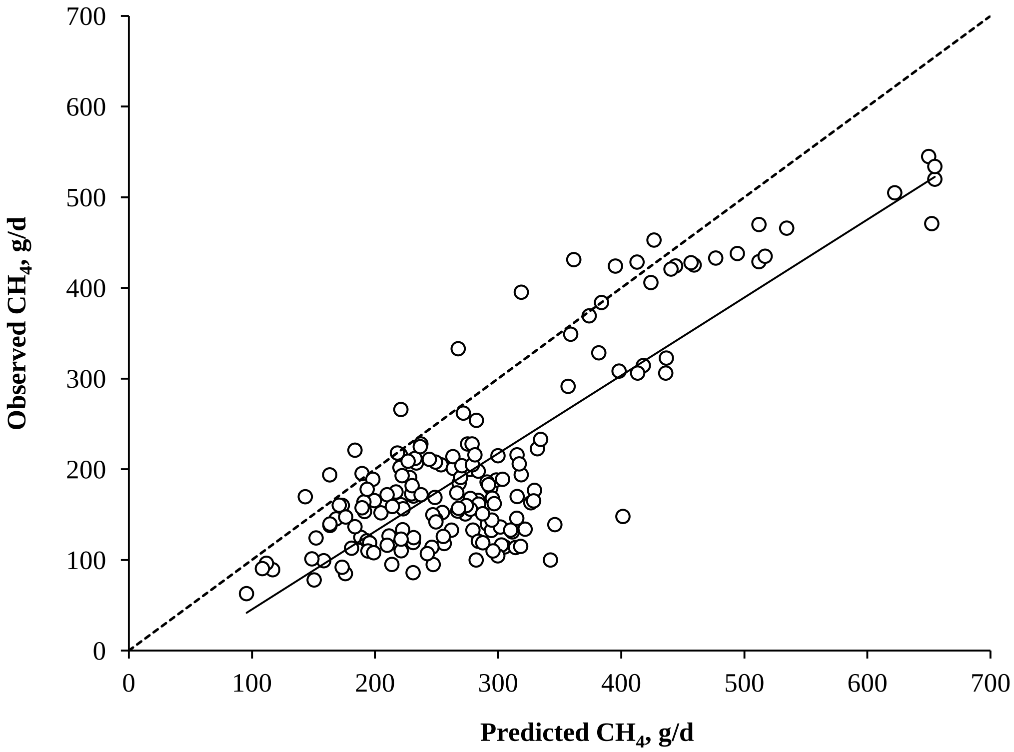


Figure 11. Relationship between observed methane (CH_4) from the validation dataset in Chapter 2 and predicted CH_4 with the equation CH_4 (g/d) = (35.1 * DMI (kg/d) + 14.7)*1000 / 1400, modified from Yan et al. (2009). Entire line: model trendline. Dotted-line: 1:1 line

In line with this resulting tendency to over-estimate observed values from Yan et al. (2009) equation, similar trend on the results were observed after applying the NewEqGEI to data collected in Chapter 3. By using the set of equations described in Chapter 2, a significant reduction of CH_4 outputs from the cow-calf pair was observed for the 3 genotypes under study, compared with predictions mentioned in Chapter 3 (P < 0.001). This reduction was 17% (99 g/d less CH_4) in average for the 3 genotypes. Differences between genotypes were significant with either equation and no significant interactions between equations and genotypes was observed either in CH_4 from cows (P = 0.755), calves (P = 0.571) or cow-calf pairs (P = 0.860, Figure 12), reflecting that the trends of the results for inter-genotype comparison are similar.

Overall, it can be concluded from this section that the use of equations developed in Chapter 2 affected significantly the total amount of CH_4 emissions shown in Chapter 3. However, the trends of the results were similar after using either equation.

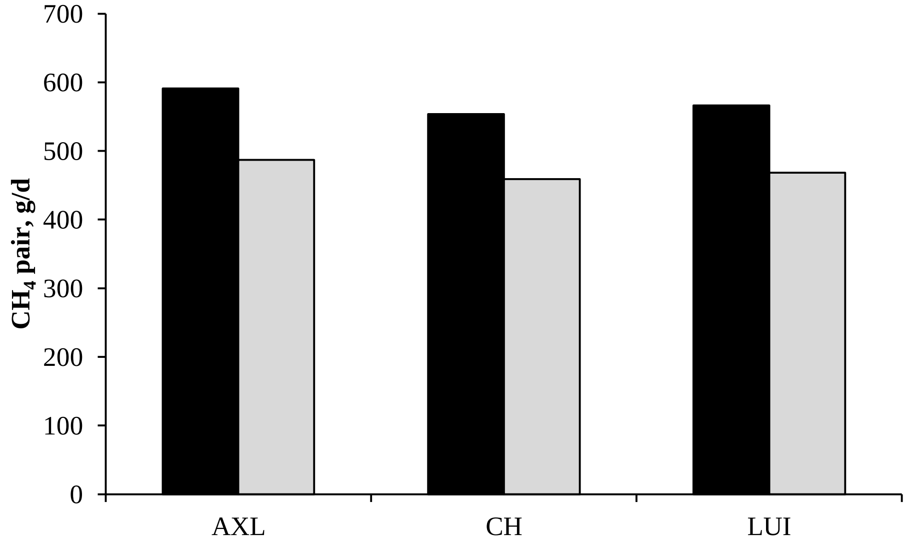


Figure 12. Mean of cow-calf pair methane (CH_4) emissions estimated with the equation CH_4 (g/d) = (35.1 * DMI (kg/d) + 14.7)*1000 / 1400, modified from Yan et al. (2009, black bars) and with NewEqGEI developed in Chapter 2 for lactating and low-concentrate animals (grey bars) each for the 3 genotypes under study (Aberdeen Angus cross Limousin: AxL; Charolais: CHA; Luing: LUI).

Chapter 4: Methane emissions from sheep and beef cattle measured with the Laser Methane Detector

Adapted from: Ricci, P., Duthie, C-A., Hyslop, J., Houdijk, J., Roehe, R., Rooke, J., Waterhouse, A. Methane emissions from ewes and steers measured with the Laser Methane Detector are correlated with respiration chamber measures. Article prepared for publication in Journal of Animal Science.

In this chapter I was responsible for the experimental design and data collection with the Laser Methane Detector of experiment 1, data processing and data analysis of experiments 1 and 2, and writing of the manuscript.

4.1 Introduction

Ruminants contribute significantly to global anthropogenic methane (**CH_4**) emissions. Different methods have been used for its quantification. However, available techniques are either expensive, labour-intensive or cannot replicate natural conditions and diets of livestock in practice. For instance, many natural and environmental factors may affect feed intake and CH_4 outputs, such as grazing behaviour and herbage selection, as previously mentioned in Chapter 3. The development of novel techniques able to measure CH_4 in practice is relevant to reduce the uncertainty of greenhouse gas assessments under diverse management conditions. As most of the CH_4 produced by ruminants is excreted by breathing and eructation and only 2% through the flatus (Murray et al., 1976), the Laser Methane Detector (**LMD**) has been proposed as an alternative method to determine enteric CH_4 emissions from animals in their natural environment (Chagunda et al., 2009b; Chagunda and Yan, 2011). This hand-held gas detector measures CH_4 concentrations of gaseous outputs from the mouth and nostril areas during short periods of time. The LMD is a non-invasive technique that allows detailed measurements on individual animals, that may provide advantages over other laborious field scale methods, for example the polyethylene tunnel (Lockyer and Jarvis, 1995) or the SF_6 tracer technique (Johnson et al., 1994).

Thus, there is potential to use the LMD in field-based on-farm measurement for characterization of CH_4 outputs, such as screening animals in breeding programs or assessment of alternative management or dietary options. The aim of the current work is to validate LMD-CH_4 measurements from ewes and steers against individual data for the same animals from respiration chambers. This chapter describes a simple means of analysing the characteristic outputs of the LMD so as to be biologically meaningful and to achieve a better understanding of the information obtained. As the LMD is hand held it is best suited to be used for short periods of time, then questions regarding when is the most appropriate time to perform CH_4 measurements, whether outputs are able to detect treatment effects and its potential applications in further mitigation testing are discussed in this chapter.

4.2 Materials and Methods

Two separate experiments were carried out at SRUC Beef and Sheep Research Centre (Bush Estate, Edinburgh, UK) to measure CH_4 concentration in the exhaled air from housed sheep and beef cattle with the LMD. Both experiments were approved by the Animal Experiment Committee of SRUC and were conducted in accordance with the requirements of the UK Animals (Scientific Procedures) Act 1986. In both experiments the LMD recorded CH_4 concentration using the standard 0.5 sec measurement interval and was used at 1 m distance from the mouth and nostrils area of the animal to the detector in both animal species. The week following LMD measurements, ewes or steers entered into a CH_4 measurement phase in open-circuit respiration chambers. Diets were identical throughout both LMD and respiration chamber phases.

The LMD (Tokyo Gas Engineering Co. LTD) measures the concentration (ppm/metre) of CH_4 present in the air between the target and the detector. These measurements are based on infrared-absorption spectroscopy using a class-1 laser, with a visible class-2 laser used as an aiming guide using backscattered light from diffusive-reflection targets. The wavelength of the light source is fixed on the absorption line of methane (1.6537 μm), which provides high accuracy for CH_4 measurements and avoids interferences with other gases. High sensitivity is achieved by the second-harmonic detection of wavelength modulation spectroscopy (Tokyo Gas Engineering Co. LTD). Real time CH_4 concentration measurements can be seen on the display of the detector. The collected data was stored in a memory card and later downloaded to a computer from the LMD.

Daily CH_4 outputs were measured in six indirect open-circuit respiration chambers (No Pollution Industrial Systems Ltd., Edinburgh, UK). Each chamber has an area of 25.4 m^2 and animals are loose-housed in internal pens of 4 x 3 m (length x width). Air was removed from the chambers by exhaust fans set at 50 litre/s and temperature and humidity were set at 15 ± 1°C and 60 ± 5% relative humidity, respectively. Exhaust air was sampled for gas analysis sequentially for 45 s from each chamber and CH_4 concentrations were measured by infrared absorption spectroscopy.

Animals remained in chambers for 72 h total stay to quantify their daily CH_4 emissions (g/d), with measurements recorded over the final 48 h. Measurements (every 6 min) of CH_4 concentrations were made in the mechanically ventilated air entering and leaving each chamber and exhaust air flow rate (every 30 min) corrected to standard temperature and pressure (Gordon et al., 1995).

4.2.1 Experiment 1

This experiment ran from May to June 2011. Methane concentration in exhaled air was measured on 24 Scottish Mule ewes (Blue-Faced Leicester x Scottish Blackface) between five and six years-old, weighing 68 ± 1.5 kg and each lactating with twin lambs at 29 ± 0.5 days into lactation (means ± SE). Animals were blocked in three groups by stage of lactation. In a well-ventilated shed, ewes were fed twice a day at 0800 and 1500 h with alfalfa pellets containing 9.5 MJ ME/kg DM, 180 g CP/kg DM and 520 g NDF/kg DM (Hazzledine, 2008). Two intake levels were used as treatments, *ad-libitum* (**AL**, n = 12) or restricted intake (**RES**, n = 12), the last one calculated to be 80% of *ad libitum* level.

The LMD was used once a week for 3 weeks while ewes were housed in the shed. Each day, the LMD was used for five 2-minute sampling periods per animal in sampling periods starting at 2, 3, 5, 6 and 7 h after feeding (1000, 1100, 1300, 1400 and 1500 h, respectively; **P1** to **P5**). Eight ewes were measured each day, taking each time 30 min to complete 8 measurements. Thus, hours after feeding varied by half an hour. The ewes were restrained by a person while being measured with the LMD to maintain a constant distance of one m between the device and the animal and to avoid the laser path leaving the area of the sheep mouth/nostrils as it moved around the pen. The following day, ewes and their lambs entered the chambers in pairs (2 ewes with their lambs per chamber) where they received the same diet at 0700 h and 1500 h.

While ewes were in the shed and in the chamber, DMI was determined as the difference of weights between offered and refused feed, the last one determined before offering fresh food.

4.2.2 Experiment 2

Between August and October 2011, the LMD was used to measure CH_4 concentrations in the exhaled air of 72 crossbred finishing steers, between 15-17 months old with average BW of 677 ± 34.3 kg. The steers were either Aberdeen Angus (A) or Limousin (L) sired and bred from a two breed reciprocal crossing programme, where cattle produced are approximately 67:33 (**AxL**, n = 36) or 67:33 (**LxA**, n = 36) over the long term. Steers were fed *ad-libitum* with one of 2 contrasting complete low-concentrate (**LC**, n = 36) or high-concentrate (**HC**, n = 36) diets, consisting of either 48:52 or 8:92 forage to concentrate ratio (DM basis) for at least 6 weeks before LMD measurements.

Measurements with the LMD were taken while animals were housed in training pens before entering the respiration chambers. In this trial, the LMD was used once a day between 0900 and 1000 h for one 4-minute sampling period repeated over 3 consecutive days. Data across all 3 daily samples per steer (12 min) were combined for further analysis. The following week, steers were transferred to open-circuit respiration chambers individually to measure daily CH_4 (g/d) as in experiment 1.

In training pens and chambers feed was offered once daily between 0800 and 0900 h.

4.2.3 LMD output data

The LMD was set to take measurements every 0.5 sec thus generating a dataset of about 240 observations per ewe and 480 per steer per sampling period. Errors in the reflectance of the laser beam, which were automatically recorded and identified by the LMD, were then manually deleted from the dataset. Finally, the exact total number of observations was taken into account as a weighting variable for further analysis.

As measures with the LMD were consistently performed at 1 m distance, results of ppm/metre of CH_4 are expressed in ppm. The minimum value of concentration recorded on each sampling period was considered to be the background CH_4 concentration of the surrounding area and was then subtracted from the rest of the sample. Measurements for each ewe or steer were evaluated as series of point measurements. The resulting dataset consisted of a series of mini-peaks and mini-troughs, as described on the amplified section of Figure 13. Because the LMD measures CH_4 concentration in the volume of air between the animal and the LMD, mini-peaks and mini-troughs are observed as a result of the respiratory tidal cycle of the animal. Mini-peak values reflect the increase in concentration of CH_4 due to exhalation while mini-troughs are recorded during the diffusion of CH_4 from the column of air. With the help of an Excel® Macro, mini-peaks and mini-troughs were identified and their mean values were separately estimated for further analysis.

Apart from the normal breath cycles comprising inhalation and exhalation, the data also exhibited episodes of high CH_4 concentration (Figure 13). Biologically the CH_4 concentrations could thus be described as two fractions: (a) soluble CH_4 from the rumen and lower gut recycled through the body water, reaching the lungs and exhaled in normal breath, and (b) gaseous CH_4 emitted directly from the rumen by eructation (Murray et al., 1976). At intervals, larger CH_4 events occur, which have their own sets of mini-peaks and mini-troughs within this event (Figure 13). These larger CH_4 events are presumed to be eructation or belches and are hereafter defined broadly as eructation. The lower oscillating level is attributed to be the CH_4 emanating principally from the lungs, previously from the vascular system, being circulated by the respiration process. This presumption is supported by observations made during the experiment, as every time the animals visibly belched, the LMD recorded episodes of high CH_4 concentration on the output screen.

To differentiate these very distinct levels of CH_4 concentration observed in the LMD outputs, a 2-step processing data was applied to the databases. Firstly, 2 independent normal distributions each with different mean values and variance were fitted to each of the sheep and beef datasets. These double distributions were fitted using GenStat (11^{th} Edition) with data transformed into natural logarithm before fitting. As a large sample is needed to fit double distributions, ewes per treatment per observation period were pooled to fit the distributions, while on the beef dataset steers on the same treatment were pooled together. Therefore, two datasets for sheep (AL or RES) and two for cattle (HC or LC diet) were used for distributions fitting. After fitting the 2 distributions, cumulative probabilities of individual data points belonging to the distribution with the lower mean (the respiration-CH_4) were calculated and used as thresholds. With a given probability, thresholds were defined to separate the CH_4 from respiration from the dataset and classify the remaining higher CH_4 as eructation. Three thresholds were set at 90, 95 and 99% cumulative probability of belonging to the lower distribution to investigate the effect on the results of using higher or lower thresholds. Secondly, levels of CH_4 higher or lower than the specified threshold for each observation were systematically labelled as **eructation-CH_4** or **respiration-CH_4**, respectively using an Excel® Macro (Figure 13).

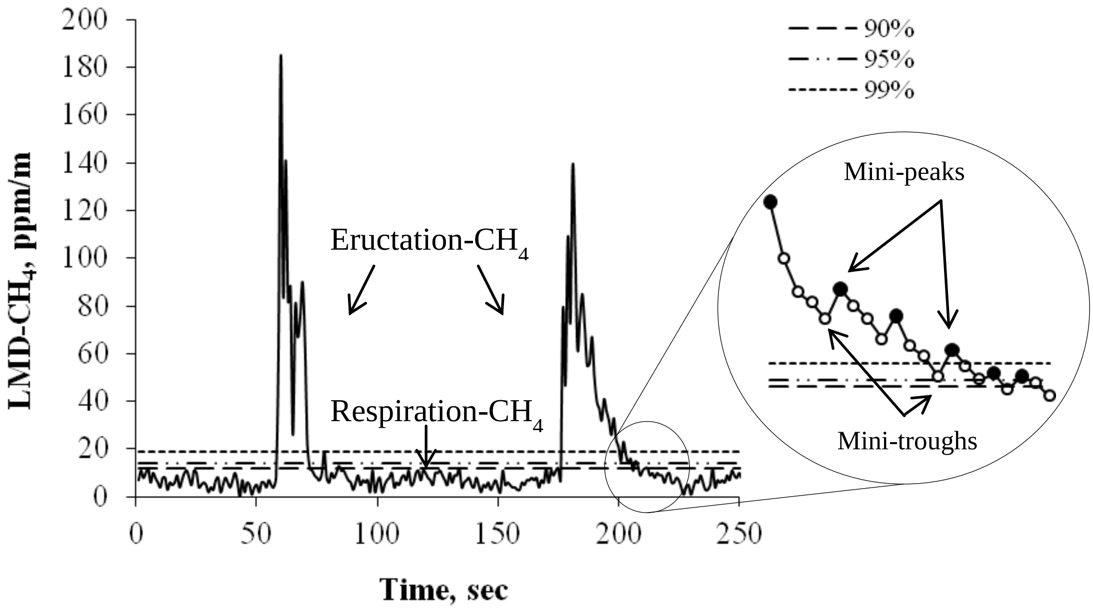


Figure 13. Example of output data (solid line) from one observation period obtained with the Laser methane detector (corrected for background CH_4) in experiment 1. Data consist of mini-peak and mini-trough values (amplified section). Values below and above thresholds of 90 (dashed line), 95 (dashed and dotted line) and 99% (dotted line) cumulative probability of the lower distribution are identified as Respiration-CH_4 and Eructation-CH_4, respectively.

4.2.4 Statistical analysis

All the observations from ewes were used for further analysis (n = 24), with each ewe per observation period as the individual experimental unit. From the beef trial, a total of 5 animals were rejected from the beef dataset due to ill health (n = 1), a faulty chamber (n = 3) and faulty LMD measurements (n = 1), leaving a dataset of n = 67 valid observations (n = 33 HC and n = 34 LC diet; n = 35 AxL and n = 32 LxA). Each steer was considered as the individual experimental unit.

As total number of observations was different from each sampling period after removing erroneous measures, total, respiration and eructation time were also considered for further analyses (Table 13). Once datasets were split into respiration-CH_4 and eructation-CH_4, the sum, number of recorded points, mean and maximum CH_4 concentration of the overall sample and within each group of events (eructation and respiration) were identified (Table 13). Additionally, mini-peaks and mini-troughs values of CH_4 concentrations both for the overall sample and within each type of event were also used (e.g. all-mini-peaks, eructation-mini-peaks and respiration-mini-peaks). All the above variables were calculated relative to the duration of the event (e.g. per min of total, respiration or eructation time, when appropriate). The proportional contribution of each group of events to the total CH_4 time and concentrations were also estimated as percentage of eructation and respiration (Table 13).

Eructation events were defined when more than 1 consecutive eructation-CH_4 point was identified. The frequencies of occurrence of eructation events, the area under the curve, minimum and maximum values were calculated and considered for further analysis (Table 13).

The area under the curve was calculated for each experimental unit using the AREA (y; x) function of GenStat (11^{th} edition), which numerically integrates the curve running through the points specified by variates y = LMD-CH_4 and x = observation, using the trapezoidal method.

Table 13. Variables estimated from the databases collected with the Laser Methane Detector

Section	Variable
Overall, respiration and eructation	Number of observations
	Minutes of observation (min)
	Mean/min
	Sum/min
	Maximum/min
	Mini-peaks/min
	Mini-troughs/min
	Area under curve/min
	Proportion Respiration mean/min
	Proportion Eructation mean/min
Eructation events	Number
	Frequency (number/min)
	Mean/min
	Minimum/min
	Maximum/min
	Area under curve/min

The LMD CH_4 concentration of the exhaled air was compared with daily mean chamber-based CH_4 outputs (g/d). Hourly means of chamber-CH_4 were also estimated. The level of agreement between measurement methods was evaluated using the REG procedure of SAS. A WEIGHT statement was used to account for different total number of observations. Potential explanatory variables were selected with the Stepwise selection process. All variables remaining in the model were significant at $P \leq 0.05$. The variables most highly correlated with chamber-CH_4 were considered first during the selection process. A CORR procedure of SAS was used for estimating Pearson's correlation coefficient.

Additionally, Lin's Concordance Correlation Coefficient (**CCC**) was calculated in GenStat (11th edition). The CCC, (predictive ability increases as it approaches a value of 1) combines the precision measurement of Pearson correlation coefficient (**r**) with a bias correction factor (**C_b**, the closer to 1 the better), a measurement of accuracy, in terms of the deviation from the origin and slope of a 45 degree line when comparing predicted vs. observed values (Lin, 1989).

Correlations and model fitting were analysed separately for each observation period on the sheep dataset with the objective of examining variation across the day to identify potentially better predictors from the LMD. During fitting the models to data from both experiments, LMD data was compared with chamber-CH_4 for the 2 dietary treatments together considering the treatment effect as a candidate variable to enter the model.

4.3 Results and discussion

In the present study a new approach for interpreting the output data from the LMD is described, to extract more information concerning the origin of CH_4. Although the LMD does not account for the CH_4 released from the flatus, this proportion has been reported to represent only about 2% of the total CH_4 produced by the animal (Murray et al., 1976). One of the characteristics of the LMD is that it provides detailed information about the major proportion of CH_4 that is released by the animal.

4.3.1 Experiment 1: understanding outputs from the LMD

The overall mean background CH_4 concentration across the study was 5.6 ± 0.17 ppm. The composition of dry unpolluted air contains 1.6 ppm of CH_4 (Brimblecombe, 1995). The higher concentration of CH_4 recorded with the LMD in the shed environment could be as a result of the presence of 36 ewes in the same environment (some of the ewes in the shed were not used for the experiment described here). The importance of segregating the collected data into respiration and eructation was confirmed during the experiment. Just after animals visibly belched, CH_4 concentrations rose rapidly to values far above 20 ppm. Moreover, the LMD was able to detect more eructation events than seen by the operator while performing the measurements. However, after a peak of eructation, other mini-peaks of decreasing but still high concentrations are recorded by the LMD. It is possible that these peaks (which are high, but not as high as the maximum peak in the eructation event) recorded by the LMD belong to smaller mini-eructation events or is CH_4 that the animal is breathing out, combining the normal respiration levels of exhaled CH_4

with the re-breathed plume from the main eructation. It could also be CH_4 remaining in the air passages from eructation and then cleared or washed out by subsequent breath cycles. Most likely, it is a combination of all these possibilities. Eructation events were previously described by Garnsworthy et al. (2012) as *"a rapid rise of CH_4 followed by an exponential decay"*. However, in the study mentioned, the authors did not consider lower levels of CH_4 emissions and rather used a baseline of 200 ppm focusing only on CH_4 from eructation events for further analysis.

In the current work, mini-peak CH_4 concentrations were comparable with the results for dairy cattle presented by Chagunda et al. (2009) and Chagunda and Yan (2011). However, these previous studies did not separate the values into respiration or eructation events. For instance, Chagunda et al. (2009) used the average of the peak values for all the breath cycles to determine the enteric CH_4 output of the individual cows regardless of whether that measurement was from breathing or eructation.

By pooling observations of ewes on the same treatment per period combination, samples of an average size of 3138 data points were used to fit double normal distributions to the dataset (Table 14). Although the distribution fitting exercise provided a single mean and standard deviation value, hence no statistical tests were performed; some interesting results were observed and described here. For instance, mean values of the higher distribution were observed to diminish over time for RES but not for AL ewes. The RES ewes showed a slight increment on the mean CH_4 concentration of the lower distribution up-to P3. This time corresponds to 4 to 5 h after morning feeding and agrees with results mentioned previously from a study using ruminal infusions of radioactive CH_4 (Murray et al., 1976).

Table 14. Mean ± standard deviations of double normal distributions fitted to CH_4 concentration (ppm) emitted from lactating ewes for each combination of treatment (ad-libitum vs. restricted intake) and observation periods. Lower distribution attributed to respiration levels and higher distribution attributed to eructation methane.

Periods[1]	*Ad-libitum*			Restricted		
	Lower distribution	Higher distribution	n[2]	Lower distribution	Higher distribution	n
P1	6.5 ± 1.5	18.4 ± 3.9	2982	6.9 ± 1.6	21.2 ± 3.7	3122
P2	7.0 ± 1.5	18.8 ± 3.4	3176	7.0 ± 1.7	15.0 ± 3.6	2953
P3	6.2 ± 1.6	16.4 ± 3.8	2922	8.2 ± 1.7	14.8 ± 3.2	3316
P4	6.6 ± 1.5	17.4 ± 3.6	2968	7.2 ± 1.5	13.1 ± 3.3	3230
P5	6.1 ± 1.5	17.0 ± 3.5	3208	7.0 ± 1.5	14.6 ± 3.0	3505

[1]Observation periods (P1 to P5) performed at 2, 3, 5, 6 and 7 h after feeding.
[2]Sample size used to fit distributions. Observations were recorded every 0.5 sec.

It was assumed in the present study that values below a given cumulative probability of the lower distribution belong to respiration-CH_4 and can be used as a threshold to separate these levels from higher sporadic episodes believed to correspond to eructation-CH_4. Using the 99% probability of the lower distribution as a threshold to separate respiration from eructation levels, maximum values recorded during eructation events ranged from 23 to 1634 ppm of CH_4. The number of eructation events detected ranged from 0 to 6.4 events/min and were not different between periods or treatments (P = 0.348 and 0.964, respectively). The mean area of eructation events ranged from 22 to 2492 ppm/min and only a tendency was observed to differ between treatments (557 ± 61.9 vs. 421 ± 51.0 ppm/min for AL vs. RES, respectively; P = 0.091). Two out of the 24 ewes in the experiment did not present eructation during one of the 5 sampling periods. For these two ewes, respiration events had an average CH_4 concentration of 4.1 ± 0.57 ppm with the mean maximum value being 10.5 ± 0.50 ppm.

Screening the dataset with a boundary of different cumulative probability of the lower distribution resulted in diverse proportions of eructation- and respiration-CH_4 (Table 15). Although the resulting thresholds were a single value, hence no statistical differences were tested; it is interesting to mention 2 main responses. Firstly, RES ewes had higher thresholds of respiration-CH_4 than AL fed ones, for each of the 3 defined levels of probability. Secondly, changes in the thresholds levels over time (P1 to P5) were observed, these responses also varying between treatments. For the AL ewes, respiration levels were higher on P2, this trend being clearer on thresholds defined at 99% cumulative probability. A similar response was observed in RES fed ewes. However, in this treatment respiration-CH_4 levels peaked in P3 and differences with other sampling periods were more accentuated than in AL ewes (Table 15).

Table 15. Methane concentration levels (ppm) recorded with the Laser Methane Detector for each treatment and period combination used as thresholds at 90, 95 and 99% cumulative probability of the lower normal distribution fitted to the dataset of experiment 1.

	Ad libitum			**Restricted**		
Probability, %	**90**	**95**	**99**	**90**	**95**	**99**
P1[1]	11.0	11.9	16.4	12.9	16.0	23.1
P2	11.9	14.0	18.9	12.9	16.0	25.0
P3	11.0	12.9	18.0	16.0	20.1	32.1
P4	11.0	12.9	16.9	11.9	14.0	16.9
P5	10.0	11.9	16.0	11.9	14.0	18.9
Respiration, %	12 ± 5.2	11 ± 4.6	10 ± 4.0	15 ± 7.5	14 ± 7.1	12 ± 6.3
Eructation, %	88 ± 5.2	89 ± 4.6	90 ± 4.0	85 ± 7.5	86 ± 7.1	88 ± 6.3

[1]Observation periods (P1 to P5) performed at 2, 3, 5, 6 and 7 h after feeding.

The proportions of CH_4 emitted by respiration and eructation have been previously reported to be 17 and 83 %, respectively (Blaxter and Joyce 1963). According to Murray et al. (1976) between 84 to 91 % (mean 87 %) of the CH_4 released from the mouth and nostrils of the animal is released from the rumen by eructation, while between 9 to 16 % (mean 13 %) of CH_4 is produced in the lower-gut where 89 % of that (11 % of the total CH_4) is re-cycled through the lungs via blood stream and eliminated by respiration. The method by which the data were separated in the present study into eructation and respiration levels of CH_4 took account of this previous knowledge. The proportions of respiration- and eructation-CH_4 observed for individual ewes in the present study using probability thresholds had a wider range of values than those mentioned in the literature. Reasons of this difference could be explained by the larger number of animals used in the present experiment and the 2 diverse feeding methods that may have affected the dynamic of CH_4 emitted over the day. Further sampling with the LMD took place over a relatively short period of time. According to Blaxter and Joyce (1963) eructation-CH_4 was proportional to total CH_4 emitted and the respiration to eructation-CH_4 ratio was not affected by the level of intake. However, these authors measured "eructation-CH_4" using gaseous chemistry and as the difference between total CH_4 from chamber measurements and eructation samples collected from tracheotomised sheep. Thus, it is probable that LMD provides more sensitive information regarding changes of eructation events over time that reflect treatment effects not detected in previous studies. However there is a limitation to translate these measures into amounts of gas emitted as knowledge of volumes of exhaled air is unknown.

On AL ewes, higher mean CH_4 concentrations in the lower and higher distribution (Table 14) and respiration thresholds (Table 15) were observed in P2, whereas the same response was observed in P3 for RES fed ewes; reflecting that the fermentation levels may be affected by the feeding regime used on this experiment resulting in a different dynamic of the digestive process (Figure 14a). At the moment, no other method can describe this variation on the respiration-CH_4 level. Therefore, validating this potential advantage of the LMD to differentiate for respired CH_4 with simultaneous measurements of animal physiological behaviour (e.g. rumen contraction types, respiration rate) is urgently needed. Applying the LMD in further studies of the fermentation process over short periods of time could provide a less invasive, less costly, less laborious tool to investigate effects of nutritional treatments.

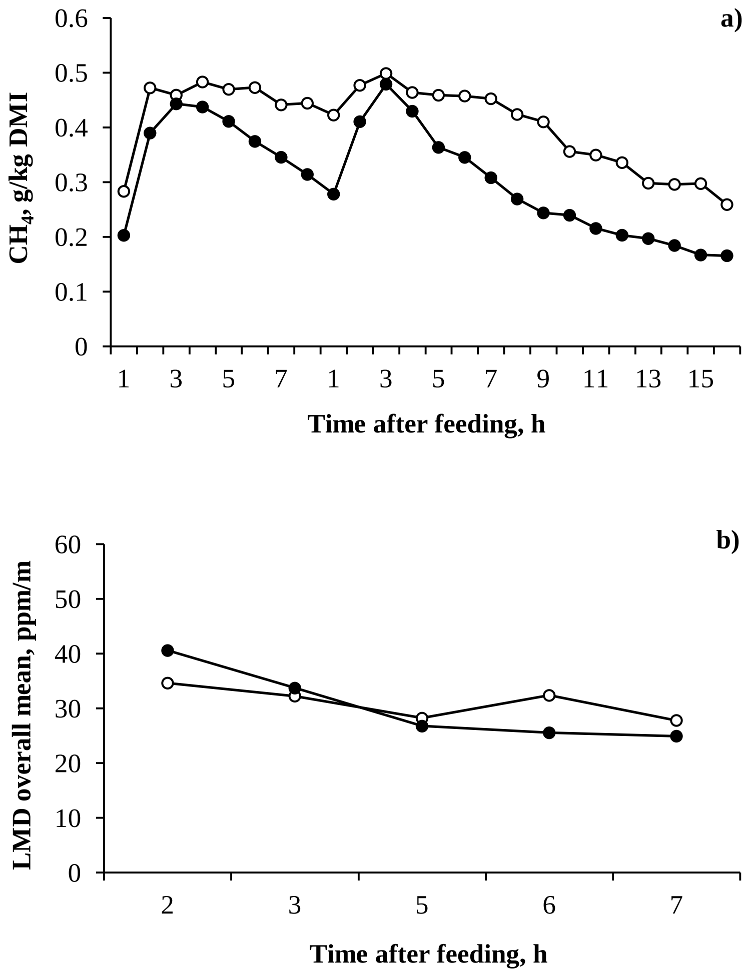


Figure 14. Methane outputs from *ad libitum* (AL, opened circles) and restricted (RES, closed circles) fed ewes measured with a) respiration chambers over the day, and b) Laser Methane Detector (LMD) over 5 observation periods.

4.3.2 Experiment 2: applying the analysis method to an independent dataset

The method of analysis of LMD outputs developed from sheep observations mentioned above was applied to an independent database of LMD measurements collected from indoor fed finishing steers. The overall mean background CH_4 concentration on this cattle experiment was 2.6 ± 0.09 ppm. This value is comparable with the CH_4 content in the atmosphere (Brimblecombe, 1995). Mean and standard deviations of the distributions fitted to this dataset independently for each treatment were comparable with those mentioned for experiment 1.

Based on 99% probability, maximum values for respiration and eructation ranged from 18 to 21 and from 29 to 2016 ppm of CH_4, respectively. Although not statistically proven, after fitting a double normal distribution, thresholds were observed to be higher for LC compared with HC fed steers (Table 16). Thresholds were similar to those observed on experiment 1 for RES ewes and observation P1 (at 2 h after feeding for both species). Proportions of CH_4 from respiration and eructation observed in the present study (Table 16) are in agreement with studies mentioning up-to 91% of CH_4 from eructation (Murray et al., 1976). Within this range, LC steers had higher proportion of eructation-CH_4 than HC steers for all the 3 thresholds levels investigated. Observed eructation events ranged from 0 to 7.7 events/min. Low-concentrates fed steers had a significantly greater number of eructation events (5.07 ± 1.32 vs. 3.65 ± 0.95 events/min, respectively; $P < 0.0001$) and each eructation event of a larger mean area, compared with HC steers (188.6 ± 8.3 vs. 135.9 ± 6.4 ppm/min, respectively; $P < 0.0001$).

Table 16. Mean ± standard deviation of the double normal distributions fitted to each treatment dataset of experiment 2 (high vs. low concentrates), thresholds for separating respiration- from eructation-CH_4 levels at 3 levels of cumulative probability (90, 95 and 99%) and proportion of CH_4 from these 2 origins as a result of application of thresholds.

Distributions	**High-concentrates**			**Low-concentrates**		
Lower, ppm[1]	6.9 ± 1.6			7.1 ± 1.6		
Higher, ppm	15.3 ± 3.6			29.6 ± 3.7		
Sample size	46,372			47,564		
Probability, %	**90**	**95**	**99**	**90**	**95**	**99**
Thresholds, ppm	12.9	15.0	20.9	12.9	16.0	22.0
Respiration, %	13 ± 5.4	13 ± 5.2	12 ± 4.6	9 ± 4.7	10 ± 4.2	10 ± 3.2
Eructation, %	87 ± 5.4	87 ± 5.2	88 ± 4.6	91 ± 4.7	90 ± 4.2	90 ± 3.2

[1]Lower and higher normal distributions fitted to the each treatment on the dataset (n=sample size).

4.3.3 Laser Methane Detector and respiration chambers

4.3.3.1 Experiment 1: lactating ewes

Daily mean chamber-CH_4 outputs from paired ewes was significantly higher for *ad-libitum* compared to restricted fed ewes (109.7 ± 3.1 and 83.2 ± 4.7 g/pair/d, respectively; $P = 0.0008$).

As sheep entered chambers in pairs (n = 12), the LMD observations were summed to be comparable with the CH_4 output per pair obtained from chambers. Correlations between chamber-CH_4 and the overall mean LMD values were poor either for the whole dataset (r = 0.19) or per treatment (r = -0.005 and 0.31 for AL and RES, respectively). Apart from P3, correlations between mean LMD and chamber-CH_4 per observation period were also very poor (r = -0.05, 0.008, 0.53, 0.44, 0.21, for P1 to P5, respectively). Mean-LMD did not explain significant variation of observed chamber-CH_4 of the whole dataset ($P = 0.120$). Even though the relationship between these variables was significant for RES ewes ($P = 0.048$ and 0.716 for RES and AL, respectively), mean LMD explained a small proportion of the variation in observed chamber-CH_4 for RES ewes ($R^2 = 0.13$). Although the correlation of mean-LMD improved in P3, this explained only 24% of the variation observed in chamber-CH_4 ($P = 0.061$).

The most significant correlations between LMD observations and chamber-CH_4 were observed for respiration and eructation levels after applying the threshold set at 99% cumulative probability, thus these variables were used for further model fitting. The ability of LMD variables to predict chamber-CH_4 differed between observation periods. Goodness-of-fit of models based upon LMD variables only (separated with 99% probability threshold) were better for measures taken on P3 and included the effect of treatment (AL vs. RES, $P = 0.004$), respiration time ($P = 0.008$) and sum of respiration points per minutes of respiration ($P = 0.04$, Table 17).

To find further good predictors of chamber-CH_4, models including additional information regarding animal characteristics were produced. Results observed in chamber-CH_4 were predicted best by DMI (kg/d; $P < 0.001$) and eructation time (min; $P < 0.002$; Table 17, Figure 15). This model showed an improvement from the relationship between chamber-CH_4 and DMI only, and chamber-CH_4 and LMD alone (Table 17). No significant contribution was observed from animals BW ($P > 0.150$) to both models either with DMI only or with LMD only.

Applying the best-fit model based only on LMD variables, significant differences were observed between treatments, similar to that observed in respiration chamber results. Predicted CH_4 was higher for AL compared with RES fed ewes, with means of 109.8 ± 2.6 vs. 83.4 ± 4.1 g/d, respectively ($P = 0.0003$).

4.3.3.2 Experiment 2: finishing steers

In the second experiment, significant differences between diets and breeds of finishing steers were observed for chamber-CH_4, being higher for LC than HC diet (205 ± 6.1 vs. 145 ± 6.9 g/d, respectively; $P < 0.0001$) and for AxL compared with LxA (183 ± 8.6 vs. 168 ± 7.7 g/d, respectively; $P = 0.022$).

The overall mean LMD was correlated with chamber-CH_4 (r = 0.50; $P < 0.0001$). A significant effect of diet type was observed for the relationship between mean LMD and chamber-CH_4 ($P < 0.0001$) and correlations between these variables was higher for the HC than LC diet (r = 0.41 and 0.13; $P = 0.018$ and 0.460 for HC and LC, respectively). Although the relationship between mean-LMD and chamber-CH_4 was significant, an improvement of the prediction ability of the LMD was observed after processing the dataset.

As a result of the model fitting process, a significant relationship was found between observed chamber-CH_4 and CH_4 predicted with the model containing Diet, DMI, BW (kg), and eructation time recorded with the LMD ($P < 0.001$; Table 17, Figure 15). In this case, LMD together with DMI and BW improved the prediction of chamber-CH_4 in comparison to the relationship between chamber-CH_4 and DMI alone ($P = 0.971$); DMI, BW and Diet alone ($P < 0.001$) and chamber-CH_4 and LMD alone ($P < 0.001$; Table 17). Including BW to a model with LMD variables only, did not contribute to explain further variation of chamber-CH_4 ($P > 0.15$).

As expected in this dataset, chamber-CH_4 was significantly affected by diet type, as a result of the highly contrasting diets utilized. In a similar way, the model based on

LMD variables only reflected significant differences between treatments, with higher CH_4 from LC vs. HC diets (205 ± 2.3 vs. 145 ± 3.3 g/d, respectively; $P < 0.001$) and higher CH_4 for AxL compared to LxA (177 ± 6.3 vs. 173 ± 5.5 g/d, respectively; $P = 0.044$).

Table 17. Accuracy and precision of models to predict CH_4 from respiration chambers based on Laser Methane Detector (LMD) measures, animal characteristics or the combination of both. Here eructation and respiration separated with the 99% cumulative probability threshold.

Model	Variables	Methane prediction models[2]	[1]Adj R^2	CCC	r	C_b
	Sheep[3]					
1s	LMD P1	113.6 - 4.53*MaxResp + 8.47*MeanResp_mini-peak	82.9	0.922	0.925	0.997
2s	LMD P2	78.8 + 66.7*EructTime - 14.7*Treat	82.0	0.917	0.920	0.997
3s	LMD P3	162.4 - 13.4*RespTime - 24.2*Treat + 0.037*SumResp_mini-peak	89.7	0.959	0.959	0.999
4s	LMD P4	-0.579 + 5.85*MaxResp_mini-peak	47.7	0.706	0.734	0.963
5s	LMD P5	175.4 - 19.7*Treat - 0.034*AreaResp	78.9	0.881	0.882	0.999
6s	DMI	-20.7 + 0.012*DMI	79.1	0.871	0.891	0.977
7s	All	-15.3 + 0.008*DMI + 58.6* ErucTime_P2	91.9	0.964	0.965	0.999
	Cattle					
1c	LMD	83.2 + 49.7*Diet + 1.84*ProportionErucTime - 109.4*MeanResp_mini-peak + 97.3*MeanResp	50.4	0.690	0.724	0.953
2c	DMI, BW	280.0 - 0.419*BW + 7.78*DMI + 64.8*Diet	48.8	0.674	0.713	0.945
3c	All	217.8 + 7.20*DMI + 52.4*Diet + 5.74*ErucTime - 0.324*BW	51.1	0.707	0.736	0.961

[1]**AdjR^2**: adjusted determination coefficient; **CCC**: concordance correlation coefficient; **r**: Pearson's correlation; **C_b**: bias correction factor.
[2]Respiration and eructation variables are per respiration or eructation time (min), respectively. **AreaResp**: area under curve of respiration (ppm/min); **BW**: body weight (kg); **DMI**: dry matter intake (kg/d); **Diet**: high vs. low concentrates; **ErucTime_P2**: mean eructation time recorded during observation period 2; **ErucTime** and **RespTime**: respiration and eructation time (min). **MaxResp**: maximum CH_4 concentration during respiration events (ppm); **MaxResp_mini-peak**: maximum mini-peak CH_4 concentration during respiration events (ppm); **MeanResp**: mean CH_4 concentration during observations (ppm); **MeanResp_mini-peak**: mean mini-peak CH_4 concentration during respiration events (ppm); **ProportionErucTime**: proportion of the total time observed as eructation events (dimentionless); **SumResp_min-peak**: sum of mini-peak CH_4 concentration during respiration events (ppm); **Treat**: *ad libitum* vs. restricted intake.
[3]Observation periods 1 to 5 (P1 to P5) corresponding to observations at 1000, 1100, 1300, 1400 and 1500 h.

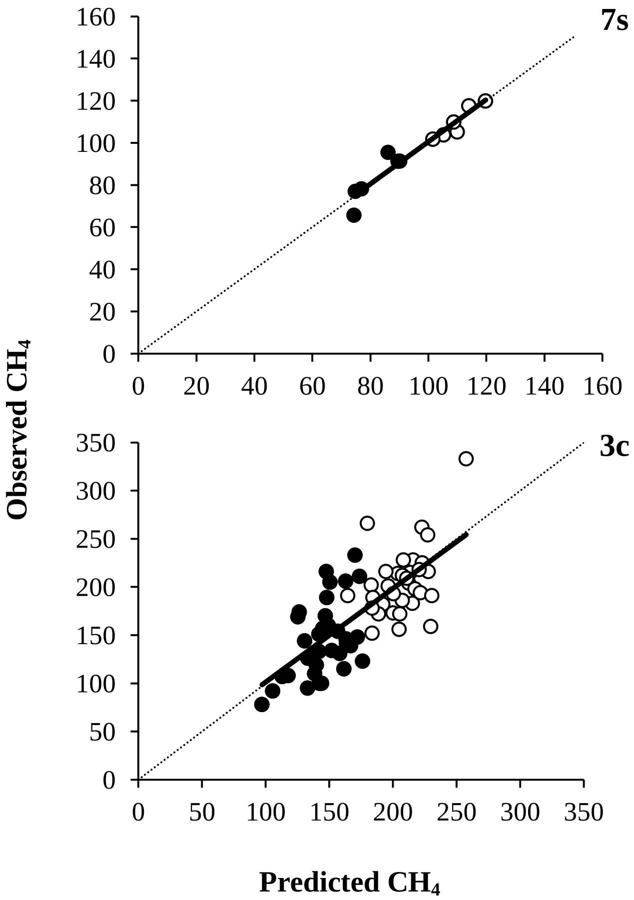


Figure 15. Relationship between CH_4 predicted with models (7s, 3c) based on Laser Methane Detector observations and observed CH_4 (g/d) in respiration chambers (Table 17) for sheep (open circles: restricted intake; closed circles: *ad libitum*) and cattle (open circles: low-concentrates; closed circles: high-concentrates). Entire line: model trendline; dotted line: 1:1 line.

Goodness-of-fit for models fitted to the sheep and beef databases were quite different. This can be explained as the quality of the collected data differed between studies. Outputs of LMD measures from sheep were less noisy that those obtained from steers, possibly as ewes were restrained by a person and movement of the head while recording measures were very rare. On the contrary, steers were restrained by their neck in a yoke, leaving free movement to the head. With steers, original data contained erroneous measurement points as a result of a lack of reflecting surface for the laser measurement. These data points represented 3 and 9% of the sheep and cattle database and were removed from the databases before further analysis.

Segregating the data from mini-peaks and mini-troughs helped to explain observed variation in chamber-CH_4, as variables related to mini-peaks were selected in 4 of 6 models fitted with LMD variables only. In the present study, more fluctuation in the LMD outputs was observed compared to those showed by Garnsworthy et al. (2012), as different measurement techniques were used. The high resolution and rapid response of the LMD to small changes on CH_4 concentrations could have contributed to the observed fluctuations. In the present study, a maximum of 6.4 and 7.7 eructation events per minute were observed for sheep and cattle LMD outputs, respectively. Lower frequency of up-to 1.8 eructation events per minute were mentioned before (Garnsworthy et al., 2012) in lactating cows while fed in the milking parlour. Although it is known that eructation events are more frequent during feeding, this difference between studies could be due to the lower threshold assumed in the present study to define an eructation event (between 16 to 32 ppm) in comparison to the assumed baseline of 200 ppm in Garnsworthy et al. (2012).

Outputs from the LMD appeared comparable to those reported using the GreenFeed system (C-Lock Technology Inc., Rapid City, SD; www.c-lockinc.com/data), with more fluctuating measures than Garnsworthy et al. (2012) and with lower and higher levels of CH_4 concentrations as observed in the present study. However, no explanation has been found of the characteristics and description of the outputs from the GreenFeed system to further discuss these results.

Correlations between models based upon LMD variables only and chamber-CH_4 (Table 17) are comparable to those mentioned before by Garnsworthy et al. (2012) using an on-farm CH_4 monitoring device in high-yielding lactating cows (R^2 = 0.79). Although better goodness-of-fit of sheep chamber-CH_4 prediction models was observed compared to cattle, in both experiments LMD outputs explained additional variation in CH_4 measured in respiration chambers than DMI alone (Table 17). This result indicates that there is more variability in observed chamber-CH_4 that cannot be explained by the level of intake of an animal recorded with respirometers, currently the best method for acquiring quantitative data on CH_4 emissions.

In both experiments it was observed with the LMD that respiration-CH_4 tended to have the opposite response than chamber-CH_4, being higher for RES ewes compared to AL and for HC fed steers compared to LC. Methane emitted in normal breath is related with soluble CH_4 that has been recycled in blood (Murray et al., 1976). Methane levels in blood are not commonly measured. In one study, an opposite trend was observed between CH_4 concentration in blood and CH_4 gas emission measured with the SF_6 tracer technique (Ramírez-Restrepo et al., 2010). This could suggest that the level of CH_4 from respiration could reflect the intensity of feed fermentation throughout the digestive tract. Feeds with longer retention time in the rumen may not have the chance to be further fermented in the lower gut (in these experiments AL ewes and LC steers), whereas those passing more rapidly through the rumen do (RES ewes and HC steers).

The results observed in this study for the LMD agree with others suggesting that CH_4 is highest just after a meal and then decreases over time (Blaxter and Joyce, 1963). A similar response was observed with LMD measures. Lower variation in CH_4 means of the lower distribution (respiration) was observed between observation periods (Tables 12 and 14). Methane emissions from the lower gut are likely to be more constant and to be buffered from time-based events such as feeding. This would suggest that the overall decrease of CH_4 over time is related to a larger reduction on eructation process. The differences observed over the day also raise questions of when the appropriate moment to characterize diets and animals is and which is the best indicator of the animal status. From the LMD models fitted, it was observed that better goodness-of-fit were obtained with variables measured on period 2 and 3, from 1100 to 1300 h. With feeding time at 0800 h, this indicates that chamber-CH_4 was better predicted from LMD measures from 3 to 5 h after offering fresh food.

Overall, the LMD could not actually predict quantities of CH_4 as measured in chambers. The LMD was developed as a monitoring devise for its application in other industries and with the objective of detecting leakage of CH_4 or concentration levels in landfills, for example. Its application for animal experimentation was described for the first time by Chagunda et al. (2009b) who utilised the LMD in dairy cows. In the present study, the direct utilization of LMD outputs did not provide enough information on the trends of the results. However, this study has shown that after processing the data collected with the LMD, it correlated well with chamber-based CH_4 measurements and thus was able to predict relative differences between treatments. The main weakness of the LMD is that it measures only concentrations, and without a means of calibrating data output against daily CH_4 production as for example by respiration chambers its main value would be comparative between diets, animals and systems in terms of ranking. The highly responsive nature of the concentration measures nevertheless enable a variety of information to be gathered, not feasible with measurement techniques with longer time intervals of measurement (e.g. a full day for many SF_6 experiments) or buffered by the size of a respiration chamber. Given the nature of the exhaled plume from the animal and the data metric produced by the LMD ppm per meter a consistent methodology with stationary animals at a consistent distance is essential to ensure comparable data between data collection periods and between animals and treatments.

4.4 Conclusion

The LMD has the potential to provide detailed information about how CH_4 is released by ruminants over short periods of time. Separating the output values statistically into high and low levels of CH_4 related with emissions from eructation and respiration, could potentially provide complementary information related to the dynamics of the CH_4 production in the fermentation process. Characteristics collected by LMD improved the prediction models of daily CH_4 outputs, suggesting that there is more variation of CH_4 emissions that are independent to the level of intake. This study suggests that the LMD data can prove useful in ranking animals and differentiate effects of different feeding regimes and diets. However, without a validation process the LMD was unable to provide an estimate of quantity of CH_4 emissions as neither measurement nor estimates of volumes of exalted and belched air were available. As well as additional studies relating LMD measures to daily CH_4 outputs where quantitative estimates of CH_4 are required, further assessments of the LMD should be performed in relation to measurements at the ruminal level and complemented with animal behaviour in order to validate these additional advantages.

Chapter 5: Relative impact of greenhouse gas mitigation options under diverse simulated beef farming systems

In this chapter I was responsible for designing and running the new model, extracting data, data analyses and writing of the manuscript.

5.1 Introduction

A variety of options to improve the biological efficiency of beef production systems have been suggested in the past decades, which share the same objective of reducing greenhouse gas (GHG) emissions (Beukes et al., 2010). Diverse GHG mitigation options have been reported in the literature claiming different reduction potential (Reynolds et al., 2010). For instance, the use of selected beef breeds of higher performance, improved quality of sown pastures, controlled application of inorganic fertilisers, reduced length of the young cattle finishing phase and use of higher levels of concentrates and dietary additives, constitute some of the most relevant management alternatives that have been mentioned to have an important GHG reduction potential (Moran et al., 2011).

A number of studies on GHG mitigation alternatives applied to animal husbandry have focused their results at the single component level isolated (e.g. the average finishing animal) from the rest of the production system. Little information is available regarding the relative contribution of diverse management alternatives and their interactions to GHG reduction at the farm level. Moreover, the relative importance or mitigation effect of management alternatives applied to production systems of diverse characteristics with varying opportunities to intensify their management and technology application is not totally understood. Diverse types of land such as improved lowland or rough hill grazing, with very differing soil, climate and vegetation cover are used for beef farming in the UK. Together this leads to great differences in grassland quality and therefore potential animal feed quality. For example, in Scotland, 85% of the land is classified as less favoured area; grasslands represent 82.4% of the agricultural area and 70.4% of the grassland area is rough grazing (Waterhouse et al., 2011). This rangeland type pasture holds much of the landscape and wildlife interests in Scotland. Thus, some management options are likely to have an impact on the biodiversity of these vulnerable habitats, through changes in stocking rates on hill semi-natural vegetation. In terms of food security these management strategies affect the returns of human-edible food, and these consequences are often not considered in GHG mitigation studies.

This chapter sets out to study the relative importance of a set of suggested GHG mitigation alternatives under beef production systems across a range of intensities of management and wide range of land type from intensive sown pastures to rough hill grazing. Further, it describes interactions and effects on the overall carbon footprint, productivity of the systems, returns of human-edible food and their potential impacts on biodiversity conservation.

Combining aspects studied in the previous chapters of this thesis, an upland beef farm containing suckler cows and finishing young stock was simulated to study the impact of the combination of management options on the final productivity of the system and their environmental implications. A simulated farm was used to represent typical farming conditions of beef systems in the UK. In the first instance, diverse levels of resource use intensity and management strategies were compared combined with the use of either a pure breed of cattle or a selected crossbreed of higher performance in a set of different farming '***systems***'. Furthermore, applications of alternative mitigation options were studied in a set of '***strategies***' applied to previously simulated farming systems.

5.2 Materials and methods

With the objective of representing alternative farming systems most used in Scotland, the SAC-C Calculator (RBU, 2011) was used to predict GHG from beef farming systems. This static and deterministic model estimates emissions from the whole-farm largely based on the IPCC (2006) Tier 1 approach and is designed for use in on-farm consultancy. However, the SAC C-calculator does not account for important interactions between the quality of the feed and its intake, which are major determinant of GHG emissions of ruminants (Johnson and Johnson, 1995). Nor does it deal well with fine details of animal number changes and different feeding regimes over time. In the present study, improvements compared to the SAC-C calculator were included in a separate beef sub-model or module to estimate emissions from the beef enterprise of the farm. Thus, a specifically constructed bespoke model for the beef herd was constructed to represent improvements on CH_4 prediction, number of animals and diet over the year, and interactions between animal performance, diet quality and intake, and GHG emissions. This model was combined with the existing SAC C-calculator (RBU, 2011) which was used to estimate CO_2 and N_2O emissions from soils management and energy use in the simulated systems. In combination they provided a sensitive model for the beef part of the system, together with a N_2O model for land-based GHG and a standardised approach to deal with energy use. These models are further described in a model section below.

Alternatives for GHG mitigation were compared in the form of "what-if" questions, in order to analyse the relative impact on each of these alternative management under simulated diverse farming **systems**.

5.2.1 Simulated beef farming systems

Simulations were based around a hypothetical case study farm which was then subject to a variety of management options representative of Scottish beef farming conditions. All simulated farms consisted of 338 ha, with 80% of the land (269 ha) classified as rough grassland such as hill semi-natural vegetation for grazing use only, and 69 ha as improved land that can be used for grazing and cropping. In this study, the amount of land and its proportion of hill and lowland were found to be that required to sustain a herd of 100 cows of a baseline system, described in the following section. To focus purely upon the relationships between beef cattle, grassland and a simple cereal crop scenario, the farm was restricted to a beef herd, associated grassland and barley.

All the beef breeding-finishing systems were based on a spring calving herd simulated over 1 year. Calves were born from March to April and weaned in September. After calving, different land use management and indoor cattle finishing diets were compared under a variety of scenarios described below.

For all the scenarios under study, it was assumed that when not grazing, replacement heifers and mature and primiparous cows were fed indoors with low-concentrate based diet (**LC**). Culled cows were assumed to be the same number as replacement heifers less the mortality rate of the breeding herd. The slaughter weight of cull cows was assumed to be the lower recorded body weight (**BW**) of cows on each system, assuming no extra feed is needed for cull cows to gain weight. Two bulls were used on each system to supplement artificial insemination and provided natural mating in June while grazing. They were fed LC diet all year round when not mating.

For all the systems unless stated, reproductive efficiency was assumed to be 85% for first calving and afterwards 90 and 92% for cows in the hill and in the lowland, respectively; replacement rates were 20% of mature cows and mortality rates 1% and 4.5% for cows and young stock, respectively, as suggested values for hill and lowland beef systems in the UK (FMH, 2012).

The assumed constraints for modelling the alternative systems were a fixed area of land (both total land and the proportion of land that was hill) and the on-farm production of all the feeds required for cattle feeding and bedding (grass silage, barley whole-crop silage, barley grain and straw), except for maize dark grain. Maize grain, minerals and molasses constitute external inputs to the systems.

Estimated mean monthly BW and BW change (**BWC**) were based on actual data of 28 Aberdeen Angus cross Limousin (**AxL**) and 28 Luing (**LUI**) cow-calf pairs, each genotype grazing either hill (n = 14) or lowland (n = 14) grassland and over-wintering cows and calves obtained at SRUC Beef and Sheep Research Centre. Both monthly BW and BWC of other animal categories were estimated to meet either the target slaughter weight or 2/3 of mature weight of finishing cattle and heifers at mating, respectively.

5.2.2 Baseline system

A baseline system (**HillLUI24**, Table 18) was designed to represent extensive management conditions currently typical of Scottish beef upland farming, where stocking rates on hill vegetation is quite high at 0.4 livestock units per hectare. Under this system, after calving in April on an improved lowland pasture (inbye), lactating mature and primiparous cows go to the hill until weaning in October, when primiparous cows are brought indoors and mature cows stay in the hill for a further three months until December. All 2 year old replacement heifers graze the rough vegetation in the hill from April to December and are only brought to the inbye area for mating in June. The age at first calving was assumed to be 3 years old. The inbye pasture is utilised by young finishing cattle during the grazing season (April to September), mature and primiparous cows during calving in April and 2 year old replacement heifers for mating in June. Weaned young stock, both females and castrated males, are fed indoors with a low concentrates-based diet (**LC**) from October till April. Finishing stock (males and females not used as replacements) have access to the inbye improved intensive swards during 6 months of summer grazing and then finished inside on a LC diet to 640 kg BW at 24 months old on average (Table 19). No additives were assumed to be fed to indoor cattle. Purebred LUI cattle were assumed to be used in the baseline system. This breed is characterised for being relatively small frame, hardy and adapted to restrictive conditions in terms of weather, quality of the hill vegetation and topography.

5.2.2.1 Yields and quality of feeds

The utilization of the hill grassland was assumed to be 1.2 tonnes of dry matter (**DM**) per hectare (6 t DM/ha production with 20% utilization rate). The quality of the selected vegetation of animals grazing hill semi-natural vegetation was estimated as described in Chapter 3. Estimated dry matter digestibility (**DMD**) of the selected diet for July, August and September was used and then calculated DMD for the rest of the year based on changes relative to July and September (Table 20). The crude protein (**CP**) content of this grassland was assumed to be 96.5 g/kg DM over the grazing season, as a suggested value by MAFF (1990) for grasses with less than 8 MJ/kg DM of metabolisable energy (**ME**).

Assuming 70% utilization rate, lowland grass sward offtakes were assumed to be 7.1 t DM/ha with fertiliser applications of 250 kg N/ha (FMH, 2012). The DMD of lowland pasture dominated by *Lolium perenne* (mean ME of 10.0±1.09 SD MJ/kg DM) was obtained from Wallis de Vries and Daleboudt (1994) as mentioned in Chapter 2 and described in more detail in Table 20. These are *in vitro* digestibility values of hand-plucked samples from a highly digestible section of the mentioned pasture, which were no different from the digestibility of extrusas from oesophageally fistulated animals. The CP content for this pasture (Table 20) was also assumed as recommended by MAFF (1990).

In this baseline system, the LC diet used for winter indoor feeding consisted of 40% grass silage, 35% whole crop barley silage, 15% barley grain and 10% maize dark grains (DM basis), with an estimated diet ME of 10.1 MJ/kg DM. Barley crop yields were assumed to be 7.5 t DM/ha of grain and 5.6 t DM/ha of straw and using 180 kg N/ha of inorganic fertiliser, as given by FMH (2012). Although yield numbers are suggested by the Farm Management Handbook, they are quite high for an upland system and these are assumed as a best practice scenario.

5.2.2.2 Diesel and fertilisers

Diesel usage was estimated based on assumptions from historical data from farm surveys (SAC Consulting, personal communication), which indicates the amount of diesel used for all required operations on lowland grasslands (20 l/ha), grass silage (120 l/ha), barley (120 l/ha) and animal feeding (10 l/head total indoors period).

The total amount of farmyard manure (**FYM**) produced on farm per year was estimated by adding the amount of faeces (estimated with equation 29, Table 23) from indoor cattle with the total straw used for bedding (100 $kg \cdot head^{-1} \cdot month$ of $housing^{-1}$, FMH, 2012). The N content per tonne of FYM was assumed to be 1.5 kg (DM basis) (DEFRA, 2010). Thus, the required fertiliser was estimated to be the amount needed to achieve the target N application (i.e. 250 kg N/ha). For the grazing inbye area, this amount was corrected by the N from directly deposited manure on the field.

5.2.3 Mitigation management alternatives

Diverse management alternatives were applied to the simulated farm for their comparison against the baseline system, while maintaining the same proportion of hill and lowland area. Mitigation alternatives were simulated in 2 steps. Firstly, different hill and lowland use intensity, cattle genotype and length of the young stock finishing period were used to build different ***systems*** (Table 18) and the results compared in the form of "what-if" questions. Secondly, alternative available technologies such as use of additives, lower inorganic fertiliser, mixed grass/clover swards and the use of a more efficient cattle genotype were added to the previously built systems and referred as alternative ***strategies***, understanding a strategy as *"a plan of action to accomplish a specific goal"*.

5.2.3.1 Farming systems

5.2.3.1.1 Hill/lowland use intensity

Reduction of livestock numbers on the poor quality hill grassland has being claimed to be a straightforward solution for reducing emissions, as cattle are the main direct contributors of GHGs and low quality forage contribute to higher emissions, as described in Chapter 1. Thus, decisions related with this management option were simulated in this study. On a system with intensive use of the hill, the size of the herd is constrained by the hill area. On the contrary, it was assumed that in a system with low use of the hill and with more emphasis in the lower ground, the size of the herd is constrained by the lowland area. One of the simulation constraints was the on-farm fodder production for cattle feeding. Whenever alternative management allowed free land not used to produce forage or grazing, it was assumed this area was designated for cropping of saleable grain, acting as a land use buffer at the system level to avoid redundant land. Due to these assumptions, more cattle using the lowland area results in a change of the proportion of land designated for either livestock grazing and feed production or cropping, and the term stock:crop balance was introduced here to help understand the results. This term reflects the ratio of amount of land (ha) used for grazing and feed production (i.e. the sum of areas of hill and lowland grazing, grass for silage, and barley for silage, straw and grain used on-farm) in relation to the land (ha) designated for saleable crop production (i.e. arable land for sold barley straw and grain).

Reducing the number of cows on the hill vegetation (i.e. dry cows and 2 year-old growing replacement heifers only) results in more emphasis on the lowland sector for maintaining a bigger herd with higher requirements, resulting in an increment of the stock:crop balance of the farm, with much reduced sale of surplus barley grain. Systems adopting this management will be referred to in this chapter as **Lowland** systems, as almost all the activities are concentrated in the inbye (Table 18). In these systems, after calving in April on an improved lowland pasture (inbye), lactating mature and primiparous cows remain in the inbye area of the farm. Replacement heifers (12 - 24 month old) graze the hill from April until December together with dry mature cows from October to December and only brought to the inbye for mating in June (Table 19). On the contrary, farms described as the baseline system where hill is used by lactating mature and primiparous cows as well as dry and 2 year-old replacement heifers, are referred hereafter as **Hill** systems (Table 18 and Table 19).

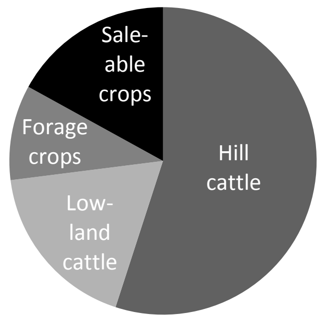
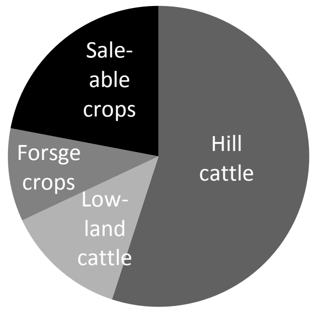
5.2.3.1.2 Cattle genotype

The use of AxL, a typical beef cattle genotype, is an option that represents an actual alternative for beef producers in the UK. This genotype has been selected for better performance (BW and BWC). However, it is characterised by a larger frame involving higher requirements under similar management conditions, compared with smaller breed types, such as LUI. Although activity of AxL tended to be similar than LUI, as described in Chapter 3, actual grazing activity in the hill and estimated quality of selected hill vegetation, together with differences on energy use efficiency (AFRC, 1993) were used for this simulation.

5.2.3.1.3 Finishing period

As an alternative management, young stock can be finished more rapidly by utilising a high concentrates grain-based diet (**HC**), reducing the access to grazing (null for males, Table 19) and assuming a lower slaughter weight. The HC diet consisted of 12% straw, 68% barley grain and 20% maize dark grain (DM basis) and estimated diet ME of 12.8 MJ/kg DM. Replacing the low concentrates silage-based diet of the baseline system by a HC diet (92% concentrates, DM basis) allows finishing entire males at 14 month old of 520 (AxL) or 500 (LUI) kg BW, respectively at slaughter. After weaning, females graze inbye pasture for 6 months and then finished with LC (Table 19) diet at 18 months of age to avoid becoming over-fat and slaughtered at similar BW as entire males. This finishing option is referred hereafter as **14** (short finishing males at 14 months old), whereas the baseline is referred to as **24** (long finishing system at 24 months old, Table 18).

Table 18. Acronyms used for different systems with combination of management alternatives

Intensive	Finishing	Genotype	Acronyms	Description	Graphic representation
Hill	Long	LUI	HillLUI24	**Baseline**. High dependence on **hill**, used by dry and lactating cows and replacement heifers. Low stock:crop balance as high saleable crop production. Use of traditional genotype (**LUI**) and stock finished at mean **24** mo old	
		AxL	HillAxL24	High dependence on **hill**, used by dry and lactating cows and replacement heifers. Low stock:crop balance as high saleable crop production. Use of selected genotype (**AxL**) and stock finished at mean **24** mo old	
	Short	LUI	HillLUI14	High dependence on **hill**, used by dry and lactating cows and replacement heifers. Low stock:crop balance as high saleable crop production. Use of traditional genotype (**LUI**) and stock finished at mean **14** mo old (heifers at 18 mo old)	
		AxL	HillAxL14	High dependence on **hill**, used by dry and lactating cows and replacement heifers. Low stock:crop balance as high saleable crop production. Use of selected genotype (**AxL**) and stock finished at mean **14** mo old (heifers at 18 mo old)	

Continue

Table 1819 (continue). Acronyms used for different systems with combination of management alternatives

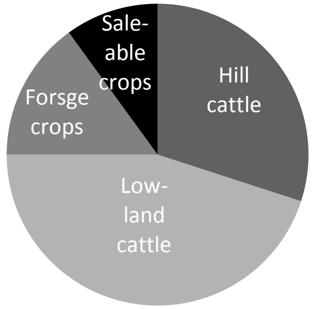
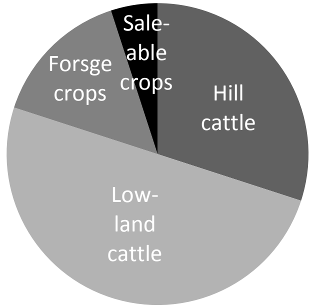
Intensive	Finishing	Genotype	Acronyms	Description	
Lowland	Long	LUI	LowlandLUI24	High dependence on **Lowland**. Hill used by dry cows and replacement heifers only. High stock:crop balance as low saleable crop production. Use of traditional genotype (**LUI**) and stock finished at mean **24** mo old	
		AxL	LowlandAxL24	High dependence on **Lowland**. Hill used by dry cows and replacement heifers only. High stock:crop balance as low saleable crop production. Use of selected genotype (**AxL**) and stock finished at mean **24** mo old	
	Short	LUI	LowlandLUI14	High dependence on **Lowland**. Hill used by dry cows and replacement heifers only. High stock:crop balance as low saleable crop production. Use of traditional genotype (**LUI**) and stock finished at mean **14** mo old	
		AxL	LowlandAxL14	High dependence on **Lowland**. Hill used by dry cows and replacement heifers only. High stock:crop balance as low saleable crop production. Use of selected genotype (**AxL**) and stock finished at mean **14** mo old	

Table 20. Land use and indoor feeding calendar for each animal type on the simulated baseline system (Hill 24) and alternative systems for a shorter finishing phase (14) and emphasised use of the lowland (Lowland)

				Females		Males		Replacement Heifers		Bulls	
System	**Month**	**Cows**	**Calves**	**6 - 12**	**12 - 24**	**6 - 12**	**12 - 24**	**12 - 24**	**24 - 36[1]**	**Cows**	**RH[2]**
Hill 24	Jan	LC[3]		LC	LC	LC	LC	LC	LC	LC	LC
	Feb	LC		LC	LC	LC	LC	LC	LC	LC	LC
	Mar	LC		LC	LC	LC	LC	LC	LC	LC	LC
	Apr	Inbye	Inbye	Inbye	LC	Inbye	LC	Hill	Inbye	LC	LC
	May	Hill	Hill	Inbye		Inbye		Hill	Hill	LC	LC
	Jun	Hill	Hill	Inbye		Inbye		Inbye	Hill	Hill	Inbye
	Jul	Hill	Hill	Inbye		Inbye		Hill	Hill	LC	LC
	Aug	Hill	Hill	Inbye		Inbye		Hill	Hill	LC	LC
	Sep	Hill	Hill	Inbye		Inbye		Hill	Hill	LC	LC
	Oct	Hill		LC	LC	LC	LC	Hill	LC	LC	LC
	Nov	Hill		LC	LC	LC	LC	Hill	LC	LC	LC
	Dec	Hill		LC	LC	LC	LC	Hill	LC	LC	LC
Lowland 24	Jan	LC		LC	LC	LC	LC	LC	LC	LC	LC
	Feb	LC		LC	LC	LC	LC	LC	LC	LC	LC
	Mar	LC		LC	LC	LC	LC	LC	LC	LC	LC
	Apr	Inbye	Inbye	Inbye	LC	Inbye	LC	Hill	Inbye	LC	LC
	May	Inbye	Inbye	Inbye		Inbye		Hill	Inbye	LC	LC
	Jun	Inbye	Inbye	Inbye		Inbye		Inbye	Inbye	Inbye	Inbye
	Jul	Inbye	Inbye	Inbye		Inbye		Hill	Inbye	LC	LC
	Aug	Inbye	Inbye	Inbye		Inbye		Hill	Inbye	LC	LC
	Sep	Inbye	Inbye	Inbye		Inbye		Hill	Inbye	LC	LC
	Oct	Hill		LC	LC	LC	LC	Hill	LC	LC	LC
	Nov	Hill		LC	LC	LC	LC	Hill	LC	LC	LC
	Dec	Hill		LC	LC	LC	LC	Hill	LC	LC	LC

continue

Table 21 (continue). Land use and indoor feeding calendar for each animal type on the simulated baseline system (Hill 24) and alternative systems for a shorter finishing phase (14) and emphasised use of the lowland (Lowland)

				Females		Males		Replacement Heifers		Bulls	
System	**Month**	**Cows**	**Calves**	**6 - 12**	**12 - 24**	**0 - 12**	**12 - 24**	**12 - 24**	**24 - 36[1]**	**Cows**	**RH[2]**
Hill 14	Jan	LC[3]		LC		HC		LC	LC	LC	LC
	Feb	LC		LC		HC		LC	LC	LC	LC
	Mar	LC		LC		HC		LC	LC	LC	LC
	Apr	Inbye	Inbye	Inbye		HC		Hill	Inbye	LC	LC
	May	Hill	Hill	Inbye		HC		Hill	Hill	LC	LC
	Jun	Hill	Hill	Inbye				Inbye	Hill	Hill	Inbye
	Jul	Hill	Hill	Inbye				Hill	Hill	LC	LC
	Aug	Hill	Hill	Inbye				Hill	Hill	LC	LC
	Sep	Hill	Hill	Inbye				Hill	Hill	LC	LC
	Oct	Hill		LC		HC		Hill	LC	LC	LC
	Nov	Hill		LC		HC		Hill	LC	LC	LC
	Dec	Hill		LC		HC		Hill	LC	LC	LC
Lowland 14	Jan	LC		LC		HC		LC	LC	LC	LC
	Feb	LC		LC		HC		LC	LC	LC	LC
	Mar	LC		LC		HC		LC	LC	LC	LC
	Apr	Inbye	Inbye	Inbye		HC		Hill	Inbye	LC	LC
	May	Inbye	Inbye	Inbye		HC		Hill	Inbye	LC	LC
	Jun	Inbye	Inbye	Inbye				Inbye	Inbye	Inbye	Inbye
	Jul	Inbye	Inbye	Inbye				Hill	Inbye	LC	LC
	Aug	Inbye	Inbye	Inbye				Hill	Inbye	LC	LC
	Sep	Inbye	Inbye	Inbye				Hill	Inbye	LC	LC
	Oct	Hill		LC		HC		Hill	LC	LC	LC
	Nov	Hill		LC		HC		Hill	LC	LC	LC
	Dec	Hill		LC		HC		Hill	LC	LC	LC

[1]Primiparous cows. [2]RH = replacement heifers. [3]LC: low-concentrates; HC: high concentrates-based diets; Hill: hill grassland; Inbye: lowland pasture.

5.2.3.2 Strategies

After defining and simulating the 8 farming ***systems*** to represent some of the management alternatives, further GHG mitigation options were included to each of the systems and analysed in a range of alternative ***strategies***.

5.2.3.2.1 Dietary additives

This mitigation option represents the ability of dietary additives to reduce enteric CH_4 production from cattle fed indoors. Large numbers of additives have been mentioned in the literature, which potentially reduce these emissions by as much as 40% (Reynolds et al., 2010). In this study, a more modest reduction of 20% is assumed by the use of alternative products added to indoor feed. For simulation purposes, it is assumed that the reduction potential of additives is constantly maintained over the period of its utilization. No embedded CO_2eq emissions were considered for additives, as this is generally variable depending on the type of additive used.

5.2.3.2.2 Level of fertiliser

Reductions in the level of fertiliser applied to the lowland swards for grazing and silage production is widely accepted as a mitigation option to reduce GHG emissions (Nyborg et al., 1997; Stewart et al., 2009; Moran et al., 2011). To represent this management option it was assumed 125 kg/ha less N would be applied compared to the baseline system. Reductions in the level of fertiliser also typically leads to reductions on the pasture yield, hence this was assumed to be 5.9 t DM/ha (including 70% utilization rate; FMH, 2012) compared to 7.1 t DM/ha with 250 kg N/ha of fertiliser of the baseline farm. When assuming the use of grass/clover swards, low and high levels of fertiliser were assumed to be 0 and 125 kg N/ha, as recommended levels for this type of swards (Frame and Laidlaw, 2011).

5.2.3.2.3 Use of grass/clover swards

Replacing lowland pure grass swards on the inbye part of the farm with grass/clover mixed pasture is presumed to lead to higher pasture yields with the same level of fertiliser (or similar yields with lower fertiliser) due to the advantage of biological nitrogen fixation of legume species. In addition, using grass/clover swards also has an effect on the quality of the forage, by increasing the energy and protein contents of the pasture (Frame and Laidlaw, 2011). For simulated strategies based on ryegrass/white clover swards, mean ME of 11 (± 0.32) MJ/kg DM and CP of 163 (± 9.36) g/kg DM were assumed (Søegaard, 2009; Frame and Laidlaw, 2011), as described in Table 20.

One limitation of the deterministic model based only on AFRC (1993) is that it lacks sensitivity to changes in protein degradability with changes in the quality of the feed. Therefore, by using the model described in this Chapter, higher energy content feeds results in a reduction of enteric CH_4 production, but this effect could be counteracted by a possible increment on the level of N excretion.

5.2.3.2.4 Improved cattle genotype

This alternative option aims to represent a hypothesised improvement of beef cattle genotype as a result of a long term breeding programme. Such an overall improvement in efficiency could be characterised in a range of ways. For this study, an improvement of 20% in the efficiency of energy used for productive functions was represented as 20% lower energy required for the assumed level of performance. Together with this, improvements of 5% on reproductive efficiencies of mature and primiparous cows and 20% reduction on replacement rates and mortality were assumed. Cumulative genetic changes of 20% and 5% in feed efficiency and reproductive efficiency were assumed over 20 years, to account for typical differences in the heritability and variability of these traits, and thus selection response expected from a similar selection intensity applied. Although these levels of improvement are high and genetic correlations with detrimental effects in other traits were not considered, the use of genetic improvement technology aims to illustrate the potential effect of a hypothetical improvement of animal efficiencies. Genetic improvement is typically incremental, but will have a wider and permanent effect at the whole system level compared with other technologies, which are single events and often limited in terms of application. However, using genetic improvement as a single, static effect enables it to be compared easily with other strategies.

Table 22. Mean dry matter digestibility content of hill and lowland vegetation and crude protein content of lowland vegetation over the grazing season assumed in the present study.

		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry matter digestibility, g/kgDM										
Hill	AxL	0.500	0.571	0.562	0.552	0.460	0.446	0.430	0.415	0.377
	LUI	0.509	0.581	0.571	0.562	0.468	0.455	0.440	0.425	0.385
Lowland	Pure grass	0.719	0.732	0.701	0.670	0.638	0.607	0.597	0.586	0.552
	Grass/clover	0.740	0.743	0.743	0.685	0.685	0.697	0.697	0.708	0.708
Crude protein, g/kgDM										
Lowland	Pure grass	119.9	150.1	119.9	119.9	96.5	96.5	96.5	96.5	96.5
	Grass/clover	163.0	148.0	148.0	162.0	162.0	179.0	179.0	163.0	163.0

5.2.4 Model

A model to estimate the carbon footprint of diverse beef production systems was built in Excel®. This is an empirical and at the same time mechanistic model. It is empirical at the individual level, as predictions are based upon factors and equations empirically developed. However, the model is mechanistic at the system level, as individual sub-systems interact dynamically to determine the final results of the system (e.g. changes in animal performance affect automatically the total area designated for crop production). Finally, the model is static and deterministic, as its estimates are obtained in a monthly basis and its parameters are not altered by a variation term.

The model comprised 3 modules, one for estimating energy requirements, feed intake and total feed budgeting, a second module for predicting CH_4 and N_2O emissions from cattle, and a third module to estimate CH_4, N_2O and CO_2 emissions from manure management, crop residues, diesel use, fertiliser application and accounted for in embedded emissions from external inputs (non-animal related emissions, Figure 16). This model included prediction equations developed in Chapter 2 and aspects of grazing behaviour studied in Chapter 3. Additional variation of enteric CH_4 predictions from intake was observed and reported in Chapter 4, potentially related to the way in which CH_4 is released from the rumen by individual animals. This extra variation, unexplained by feed intake levels, was observed to be close to 10% and was further included in an uncertainty analysis.

By utilising alternative management, either fodder yields or feed requirements of the herd were affected, hence the number of livestock possible to be reared on-farm were different. For the resulting alternative systems, the number of total calving-cows and number of hectares of each crop/inbye needed were calculated using smooth non-linear programming (N-LP) in Excel® (Solver, GRG nonlinear) in order to match the total requirements of feed from all animals on farm with the total availability from each feed, with the constraint of on-farm produced forage. This was done taking into account the total straw required for bedding and given yields of hill and inbye grassland, grass silage, and barley silage, grain and straw. The size of the herd was therefore constrained by the hill or lowland area depending on the adopted management alternative (hill or lowland intensive), allowing spare land in the lowland area to produce saleable grain and straw. The N-LP model works minimizing the balance between total feed required by the herd and available over the year. Restrictions are introduced to obtain a balance equal to zero for fodder production, whereas barley grain and straw are allowed to be in excess. In this way maintaining the hill area fixed the N-LP allows to obtain the maximum number of animals possible and the optimum land use for forage and crop production.

The third module used to estimate non-animal related emissions was derived from the SAC C-calculator (RBU, 2011). Emissions of CO_2eq associated with land use change, use of electricity, pesticides, changes of soil carbon stock, and pollution and eutrophication risk to water sources were not taken into account in this simulation.

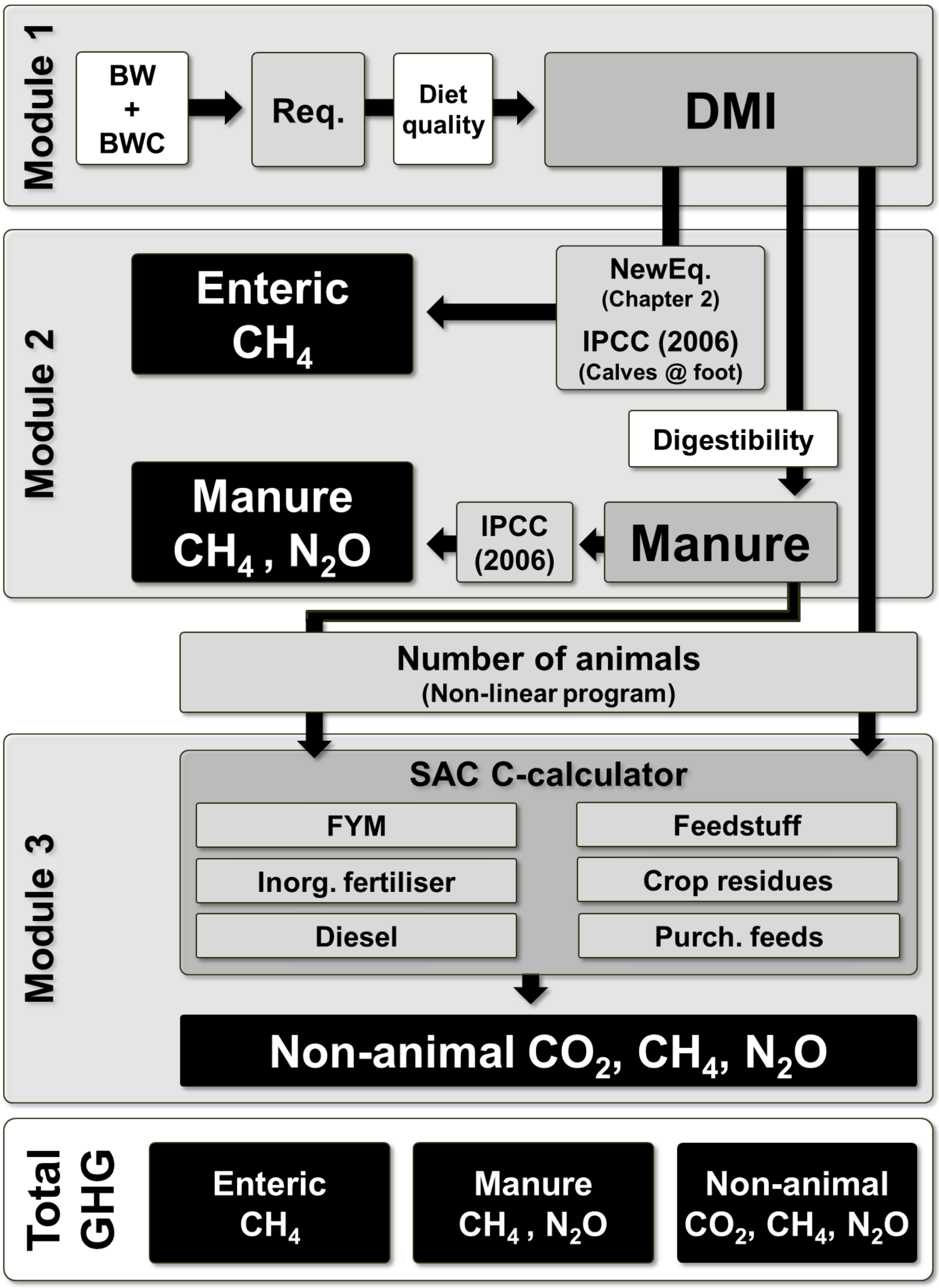


Figure 16. Model used for simulation containing 3 main modules and a non-linear program. Module 1 estimates monthly individual dry matter intake (DMI) from body weight (BW) and BW change (BWC), energy requirements (Req.) and diet quality. Methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) from animal or non-animal sources are estimated with Module 2 and 3, respectively.

5.2.4.1 Module 1: Requirements of energy, protein and feed intake

The first module used to predict energy and protein requirements and intake was based in AFRC (1993) recommendations. Total metabolisable energy requirements (ME_{total}) for each animal category were estimated by the addition of requirement for maintenance (ME_m), growth (ME_g), pregnancy (ME_p) and lactation (ME_{lac}), where appropriate (Table 21). The ME_{total} required by mature cows was estimated using the correction factor (C_L) for feeding level (L) to adjust requirements with the reduction in available ME as a result of reduced retention time of feed in the rumen at high intake rates (Equation 17, Table 21). For growing and fattening animals, ME_{total} was estimated with a negative exponential function to correct for the non-linear relationship between energy retention and energy intake (Equation 19, Table 21).

The energy conversion factor (C_a) used for estimating energy requirements for physical activity of housed and lowland grazing cattle was 0.0071 MJ/kg BW/d, following recommendations from AFRC (1993). For hill grazing cattle, observed breed specific activity patterns were used as described in Chapter 3 (Table 12). Coefficients of energy use for activity described by (Brosh et al., 2010b) were used (0.62 and 5.17 J·kg BW^{-1}·m^{-1} horizontal and vertical, respectively). Combining observed physical activity as described in Chapter 3 with adequate coefficients of energy expenditure of hill grazing cattle resulted in a C_a of 0.0114 and 0.0111 MJ·kg BW^{-1}·d^{-1} for AxL and LUI, respectively. Assumed values of correction factors for energy (C_2) and protein (C_6) requirements for growth for mature body size and sex (varying among genotypes) are described in Table 22.

For predicting energy requirements of lactation, the milk yield was assumed to be that required to provide the energy needed by calves (Milk yield * EV_l = total calves Net Energy requirements) up to a limit determined by dams' maximum milk production potential (Equation 12, Table 21). Calves at foot start eating some grass whenever the energy provided from milk does not fulfil the energy required. As described in Chapter 3, varying the milk;grass ratio of calves did not have a big impact on CH_4 emissions from the cow-calf pair, as higher CH_4 emissions from forage fed calves are counteracted by lower CH_4 emissions from the dams requiring lower energy for a less demanding lactation.

Once energy requirements are known, the feed DMI (kg/d) was estimated as suggested by AFRC (1993) as the amount of feed of a given quality needed to provide the ME_{total} required. The GE intake (GEI, MJ/d) was estimated as the product of DMI (kg/d) * GE (MJ/kgDM) content of the diet.

Requirements for metabolisable protein of maintenance (MP_m), growth (MP_g), pregnancy (MP_p) and lactation (MP_{lac}) are estimated individually and added together to predict total MP requirements for each animal category (MP_{total}). Following recommendations of the AFRC (1993) model, these requirements were estimated as described in Table 21. Different correction coefficients for protein requirement for size and sex (C_6, which considers differences among genotypes) were assumed (Table 22).

Table 23 Equations applied to predict energy and protein requirements and intake adopted from AFRC (1993).

N°	Equation[1]
Energy requirements	
1	$ME_m = (F + A)/k_m$
2	$F = C_1 * (0.53 * (BW / 1.08)^{0.67})$
3	$k_m = 0.35 * q_m + 0.503$
4	$A = C_a * BW$
5	$ME_{gl} = C_g * BW/k_g$
5	$k_g = 0.95 * k_l$
7	$k_l = 0.35 * q_m + 0.420$
8	$ME_g = (EV_g * BWC)/k_f$
9	$EV_g = \left(\frac{C_2 * (4.1 + 0.0332 * \mathrm{BW} - 0.000009 * BW^2)}{(1 - C_3 * 0.1475 * \mathrm{BWC})}\right)$
10	$k_f = 0.78 * q_m + 0.006$
11	$ME_{lac} = Milk\ yield * EV_l / k_l$
12	$Max\ milk\ yield = 8.0 * n^{0.121} * e^{-0.0048n}$
13	$ME_p = E_c/k_c$
14	$E_c = 0.025 * W_c * (E_t * 0.0201e^{-0.0000576t})$
15	$W_c = \left({W_m}^{0.73} - 28.89\right)/2.064$
16	$log_{10}(E_t) = 151.665 - 151.64e^{-0.0000576t}$
17	$C_L = 1 + 0.018 * (L - 1)$
18	$L = (ME_m + ME_{production})/ME_{production}$
19	$ME_{total} = ((F + A)/k) * \ln(B/(B - R - 1))$
20	$B = k_m/(k_m - k_f)$
21	$R = (C_4 * (EV_g * BWC))/(F + A)$
Protein requirements	
22	$MP_m = 2.30 * BW^{0.75}$
23	$MP_{BWC} = C_{BWC} * BWC$
24	$MP_g = C_6 * \left(168.07 - (0.16869 * BW) + \left(0.0001633 * (BW^2)\right)\right) * \left(1.12 - (0.1223 * BWC) * (1.695 * BWC)\right)$
25	$MP_{lac} = 13.57 * Milk\ Protein$
26	$MP_p = 1.01 * W_c * (TP_t * e^{-0.00262t})$
27	$log_{10}(TP_t) = 3.707 - 5.698 * e^{-0.00262t}$

[1]**A**: physical activity (MJ/d); **B**: correction factor for efficiencies of utilisation; $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{C_4}$ and $\mathbf{C_6}$: Table 22; $\mathbf{C_a}$: energy conversion factor for activity; $\mathbf{C_{BWC}}$: 233 or 138 g/kg BW gained or loss, respectively; $\mathbf{C_g}$: 19 or 16 MJ/kg BW for positive or negative BWC, respectively; $\mathbf{C_L}$: feeding level correction factor; $\mathbf{E_c}$: daily gravid foetus energy retention (MJ/d); $\mathbf{E_t}$: gravid foetus energy retention at time t (MJ); $\mathbf{EV_l}$: milk energy value, 3.0 MJ/kg; $\mathbf{EV_g}$: growth energy value; **F**: fasting metabolism (MJ/d); **k**: energy use efficiency **(EUE)**; $\mathbf{k_c}$: pregnancy = 0.133; $\mathbf{k_g}$: BWC of lactating cows; $\mathbf{k_l}$: lactation; $\mathbf{k_m}$: maintenance; **L**: multiple of ME_m; $\mathbf{ME_{diet}}$: dietary metabolisable energy content (MJ/kg DM); **ME**: metabolisable energy required (MJ/d); $\mathbf{ME_g}$: non-lactating cattle BWC; $\mathbf{ME_{gl}}$: lactating cows BWC; $\mathbf{ME_{lac}}$: lactation; $\mathbf{ME_m}$: maintenance; $\mathbf{ME_p}$: pregnancy; $\mathbf{ME_{total}}$: total ME required for growing and fattening cattle; **MP**: metabolisable protein required (g/d); $\mathbf{MP_{BWC}}$: for BWC; $\mathbf{MP_g}$: growth; $\mathbf{MP_{lac}}$: lactation; $\mathbf{MP_m}$: maintenance; $\mathbf{MP_p}$: pregnancy; **n**: week of lactation; $\mathbf{q_m}$: diet metabolisability (ME_{diet}/GE_{diet}); **R**: scaled energy retention (MJ/d); **t**; days since conception; $\mathbf{TP_t}$: tissue protein retention for pregnancy (kg); $\mathbf{W_c}$: calf birth weight (kg); $\mathbf{W_m}$: average dams' BW (kg).

Table 24. Coefficient for correcting energy and protein requirements depending on maturity size and sex of the animal, as recommended by AFRC (1993).

Coefficient[1]	Breed	Steers	Heifers	Bulls
C_1		1.00	1.00	1.15
C_2	LUI	1.15	1.30	1.00
	AxL	0.85	1.00	0.70
C_4		1.15	1.10	1.15
C_6	LUI	0.90	0.80	1.00
	AxL	1.10	1.00	1.20

[1]Coefficients for energy use efficiency (EUE) for maintenance (C_1) and body weight change (C_2); bias correction factor for growing and fattening cattle (C_4); and correction factor for net protein content of body weight gains (C_6).

5.2.4.2 Module 2: Emissions from cattle

5.2.4.2.1 Enteric methane

Enteric CH_4 emissions were estimated using the model obtained in Chapter 2, which considers different CH_4 emission rates for a combination of diet types and physiological stages of cattle (Table 8). Equations developed in Chapter 2 were fitted for a minimum GEI value of 66.7 MJ/d (Table 2) and weaned animals. Thus, the IPCC (2006) equation (CH_4 (g/d) = ((GEI * Ym)*1000 (g/kg))/55.65(kg/MJ)) was used for predicting CH_4 from calves at foot and when GEI was lower than 66.7 MJ/d to avoid extrapolation of the new equations.

5.2.4.2.2 Emissions from manure

As described in Chapter 1, cattle also contribute with CH_4 and N_2O emissions from faeces and urine directly excreted to the soil and during manure management.

Emissions of CH_4 from manure were predicted following the IPCC (2006) Tier 2 methodology (Table 23). Conversion factors assumed for simulation are described in Table 24. Housed animals were straw bedded during the indoor period, thus a solid storage manure management system was assumed to be used for all the systems in study.

Direct and indirect N_2O emissions from manure were estimated following the IPCC (2006) Tier 1 recommendations. The manure directly deposited by grazing animals is not accounted for direct N_2O of manure management system, but it contributes with emissions from managed soils. The same equations were used for predicting direct emissions from manure on pasture and manure management (IPCC, 2006) as at a given point in time, animals were either grazing or indoors.

Conversion factors for estimating direct and indirect N_2O emissions are described in Table 24. Indirect N_2O emissions from manure are considered for volatilization and leaching of N. The fraction of manure N that is lost by volatilization depends upon the manure management system and it was assumed to be 45% for solid FYM and 20% for manure directly deposited in the field by grazing animals (Table 24). For estimating indirect N_2O emissions by leaching and runoff, the fraction of manure N that is lost by leaching and runoff ($Frac_l$) was assumed to be 5% from FYM and 30% from manure excreted while grazing (Table 24). The 5% leaching proportion of the FYM nitrogen was obtained by the difference between the total loss of N on FYM assumed to be 50% (IPCC, 2006) and the N loss due to volatilization, assumed to be 45% (Table 24). Finally, the total N_2O emissions from manure accounted before its application to soil of FYM were estimated by adding direct and indirect emissions (equation 34, Table 23).

Table 25. Equations adopted from IPCC (2006) for estimating methane (CH_4) and nitrous oxide (N_2O) emissions from manure management and directly deposited in the field.

N°	Equation[1]
Methane emissions from manure management	
28	$Manure_{CH_4}(kg/d) = VS * B_o * MCF * 0.67 * d$
29	$VS = \left(GEI * (1 - DMD) + (UE * GEI)\right) * ((1 - 0.08)/GE)$
Direct N_2O emissions from manure	
30	$N_2O_{Direct} = (N_{ex} * EF_d) * 44/28$
31	$N_{ex} = (((DMI * CP) - MP_{total})/6.25)/1000$
Indirect N_2O (volatilization and leaching)	
32	$N_2O_{volatilization} = (N_{ex} * (Frac_v/100)) * EF_v * 44/28$
33	$N_2O_{leaching} = (N_{ex} * (Frac_L/100)) * EF_L * 44/28$
Total N_2O emissions from manure	
34	$Total\ N_2O\ manure = N_2O_{Direct} + N_2O_{volatilization} + N_2O_{leaching}$

[1]**B_o**: maximum CH_4 producing capacity (m^3 CH_4/kg VS excreted); **CP**: dietary crude protein content (g/kg DM); **DMD**: dry matter digestibility of the diet (g/kg DM); **DMI**: dry matter intake (kg/d); **EF_d**: direct N_2O emission factor from manure (kg N_2O-N·kg N excreted^{-1}); **EF_L**: N_2O-N emission factor of leached N (kg N_2O-N·kg N^{-1}); **EF_v**: N_2O-N emission factor N volatilized (kg N_2O-N·kg N^{-1}); **$Frac_L$**: manure N lost by leaching and runoff (%); **$Frac_v$**: manure N lost by volatilization (%); **GE**: dietary gross energy (MJ/kg DM); **GEI**: gross energy intake (MJ/d); **MCF**: CH_4 conversion factor of the manure management system (%); **MP_{total}**: total protein required (g·head^{-1}·d^{-1}); **N_{ex}**: nitrogen excretion (kg N/d); **UE**: proportion of energy lost in urine (dimensionless) = 0.04 or 0.02 for dietary grain content below or above 85%, respectively; **VS**: volatile solids (organic material excreted in cattle manure, kg/d); **0.67**: conversion factor of m^3 CH_4 to kg CH_4; **44/28**: conversion factor of N_2O-N into N_2O; **6.25**: protein to N conversion factor (g/g); **1000**: conversion factor of g to kg.

Table 26. Methane (CH_4) and nitrous oxide (N_2O) fractions and emission factors from manure management and their ranges of uncertainty.

	Pasture			**Solid storage**			**Source**
Factors[1]	Default	Lower[2]	Upper	Default	Lower	Upper	
B_o	0.18	0.153	0.207	same pasture			IPCC (2006), Table 10A-5
MCF	1.0	0.8	1.2	2.0	1.6	2.4	IPCC (2006), Table 10.17
EF_d	0.02	0.007	0.06	0.005	0.0027	0.01	IPCC (2006), Table 10.21 and 11.1
EF_v	0.01	0.002	0.05	same pasture			IPCC (2006), Table 11.3
EF_L	0.0075	0.0005	0.025	same pasture			IPCC (2006), Table 11.3
$Frac_v$	0.2	0.05	0.5	0.45	0.1	0.65	IPCC (2006), Table 10.22 and 11.3
$Frac_L$[3]	0.3	0.1	0.8	0.05	0.035	0.065	IPCC (2006), Table 10.22, 10.23 and 11.3
SAC C-calculator		**Default**		**Lower**		**Upper**	
EF_{vSF}		0.01		0.003		0.03	IPCC (2006), Table 11.1
$Frac_{vSF}$		0.10		0.03		0.3	IPCC (2006), Table 11.3
Diesel use		3.18		2.86		3.49	SAC Consulting (per. comm.)
Embedded CO_2eq. from external inputs[4]							
Fertiliser		7.11		6.40		7.82	Carbon Trust (2010)
Maize dark grain		340		306		374	Carbon Trust (2010)
Minerals		132		119		145	Carbon Trust (2010)
Molasses		150		135		165	Carbon Trust (2010)

[1]**B_o**: maximum CH_4 producing capacity (m^3 CH_4/kg VS excreted); **EF_d**: direct N_2O emission factor from manure (kg N_2O-N·kg N excreted^{-1}); **EF_L**: N_2O-N emission factor of leached N (kg N_2O-N·kg N^{-1}); **EF_v**: N_2O-N emission factor of N volatilized (kg N_2O-N·kg N^{-1}); **$Frac_L$**: manure N lost by leaching and runoff (kg N·kg N applied or deposited^{-1}); **$Frac_v$**: manure N lost by volatilization (kg N·kg N applied or deposited^{-1}); **MCF**: CH_4 conversion factor of manure management system (%);

[2]Ranges of uncertainty levels as recommended by IPCC (2006). For **Bo** and **MCF** an uncertainty of 15 and 20%, respectively is recommended (IPCC, 2006).

[3]**$Frac_l$** from solid storage manure default value (0.05) was estimated as total N loss from manure (0.5) minus N loss by volatilization (0.45) for this management system (IPCC, 2006). An uncertainty of 30% was assumed for this value.

[4]10% assumed uncertainty for emission factors of embedded emissions and diesel use.

Greenhouse gas emissions from contrasting beef production systems

5.2.4.3 Module 3: SAC Carbon calculator

To complete the predictions of CO_2eq emissions from the whole system, the SAC C-calculator (RBU, 2011) was used to account for emissions related to the application of organic and inorganic fertilisers, degradation of crop residues, use of diesel for cropping and indoor animal feeding related work, and to account for embedded emissions of external inputs to the system, such as fertiliser, diesel and purchased feeds (e.g. maize grain, molasses and minerals for indoor feeding, Table 24).

Emission factors and their assumed range of values used in the SAC C-calculator are described in Table 24. Emissions of CO_2eq from urea application were assumed to be 20%. No uncertainty was included in this factor as it is assumed to be the carbon content of urea on an atomic weight basis ($CO(NH_2)_2$, IPCC, 2006).

5.2.5 Carbon budget

To estimate the C footprint for each of the systems and alternative strategies, calculations were performed in 3 steps. Firstly, monthly BW and performance data was simulated. Estimates of enteric CH_4 and N_2O from manure were performed monthly and therefore sensitive to the type of diet (LC vs. HC) and grazing location (hill vs. lowland) of one individual animal of each category (i.e. physiological stage).

Secondly, estimated emissions were multiplied by the number of animals of each category. As the number of animals was variable across systems, feed budgets were estimated for the whole-herd in order to estimate the required land-use management needed (number of hectares of each forage to be grown in the lowland) to match the requirements of the herd. The number of hectares designated to each forage production is therefore a function of both animal (e.g. stocking density, genotype, efficiencies) and land productivity (e.g. type of sward, level of inorganic fertiliser application).

Once the total land allocated to fodder or crop production was estimated, input values for the C-calculator were generated. Required information for the C-calculator are number of hectares of each crop/land, total amount of organic (in this case FYM) and inorganic fertiliser applied to each crop, crop and forage yields, total allocated crops for feed, bedding or sold, total purchased feeding stuffs (e.g. supplements, additives), and total use of diesel. Finally, the SAC C-calculator predicts the total kg of CO_2eq produced by the systems and also discriminated by arable or beef sub-systems.

5.2.6 Result analysis approach

The systems under study were compared for their total CO_2eq emission potential. When referring to emissions from the beef sub-system, emissions related with the extra crop production sold outside the beef system were not considered (e.g. emissions from diesel and fertiliser needed to produce the grain sold) but they are included when referring to results from the whole-farm system.

As total number of stock was different on each scenario under study, for comparison purposes total emissions were also compared in terms of emissions per herd of 100 cows, in addition to the actual modelled herd and total farm. Total emissions were also expressed per unit of product, considering emissions and products from either the beef sub-systems or the whole-system. A unit of product for the beef sub-system was assumed to be kg of carcass assuming 59 and 55% yield (or dressing %) of live bodyweight for young finishing stock and culled cows, respectively (Bywater and Baldwin, 1980).

Human-edible returns (human-edible inputs - human-edible outputs) were also estimated and compared among different systems and strategies to highlight the importance of these systems from the food production point of view. Emissions per unit of human-edible food produced (human digestible protein from meat and grain) were estimated as mentioned by Bywater and Baldwin (1980) and using a set of assumptions regarding protein and energy contents of the food produced on-farm (Table 25).

Table 27. Human digestible energy (DE) and protein (DP) content of inputs and outputs of beef production systems. Adapted from Bywater and Baldwin (1980).

Human-edible food				
	% of BW		DE	DP
	Cull cows	Young	MJ/kg DM	kg/kg DM
Dressing	55	59		
Lean	65.5	63	7.5	0.2
Fat	14	21	35.2	-
Barley grain			15.8	0.108
Maize grain			14	0.088
Molasses			15.3	0.108

5.2.7 Uncertainty analyses

In the first instance, the model was run deterministically and results of productivity, land-use and GHG emissions were compared in more general terms. Secondly, uncertainty on GHG emission factors, animals' performance and DMD of grazed inbye and hill grasslands was included to illustrate the effect of biased assumptions and predictions in the simulation. This takes forward the approach used in Chapter 3 where sensitivity /uncertainty analyses were performed.

Uncertainty analyses were performed to identify the effect of potential changes on assumptions that are likely to have high variability. Individual animal variation was not considered in the first simulation but rather mean values of animals BW and performance were used for estimating food requirements, CH_4 and N_2O emissions of each animal category. In reality there is considerable variation about the main factors driving GHG calculations, BW, BWC and productivity. In the same way, high variability is expected in the quality and quantity of production and utilisation of the grasslands with major impacts on both performance and GHG emissions. Thus, a 10% variation on both animal performance and digestibility of the grasslands was assumed to represent their effect on the uncertainty of the results. This 10% variation was observed to be reasonable in both source of data used for diet DMD and animal performance. It is also well known there is large uncertainty on GHG emission factors (as described in Chapter 1). Thus, uncertainty ranges recommended by IPCC

(2006) were considered (Table 24). For enteric CH_4 equations developed in Chapter 2, a ± 10% variation was considered.

A Monte Carlo simulation was performed with the final CO_2eq emissions per unit of product of each system with the help of Crystal Ball Oracle®. This software allows performing repeated random sampling of thousands of iterations to obtain samples from a probability distribution. In this study a triangular distribution was used, which was defined by the mean, lower and upper bands of the results after running the model 3 times with the mean and extremes values, respectively. Means and standard deviations of the probability distributions were used to find the cumulative probability function of a range of values for each of the systems. This procedure was repeated for two more key issues by taking into account the variation on DMD and performance only, and the variation of emission factors only with the objective of estimating the proportional contribution of each of these factors to the total uncertainty.

5.3 Results

The results of BW and performance of all animal categories in a herd are shown in Table 26. Numbers of animals in the baseline and alternative systems are presented in Table 27. The amount of land designated to each crop, the production of FYM and external inputs to the system are summarised in Table 28. Productivity, use of human-edible inputs and returns from the baseline and alternative systems are shown in Table 29.

Systems with more emphasis on the use the hill grassland have more available land in the low ground. This land can then be used for different purposes. It was assumed in this study that this extra land was suitable for extending crop production, thus converted into saleable grain. Therefore, results of GHG emissions and productivity are presented separately in two steps; firstly emissions and production of the beef enterprise and secondly total emissions and productivity of the whole-farm, including emissions and production from cropping the spare land available.

5.3.1 Alternative systems

5.3.1.1 Use of more efficient genotype

The use of AxL cattle, a larger genotype implied greater energy and feed requirements of the herd driven by their heavier individual weights (Table 26). Compared with the baseline system (HillLUI24), farms with AxL cattle were able to maintain slightly fewer total breeding cows (Table 27), constrained by the fixed hill grazing area available for summer grazing (Table 28). With fewer total animals on-farm, less forage was required from the lower ground and more land was allocated for saleable crops decreasing the ratio of stock to crops in the stock:crop balance (Table 28). With slightly less young stock of the same slaughter weights for both genotypes, but bigger culled cows a Hill24 farm with AxL cattle had similar carcass production than the baseline system (Table 29).

Total emissions of $CO_2eq\cdot year^{-1}$ and $CO_2eq\cdot herd^{-1}\cdot year^{-1}$ from the beef enterprise of the HillAxL24 system were slightly lower than the baseline (Table 30, Figure 17). Lower emissions of CH_4 from enteric fermentation, N_2O from manure and organic and inorganic fertilisers, crop residues, CO_2 from diesel, fertiliser and purchased feeds were observed (Figure 19), as a result of use of fewer animals and less external inputs required (fertiliser, imported feed and diesel) for the beef enterprise of the farm (Table 28). As the productivity of HillAxL24 compared with baseline was unaffected, emissions per unit of product (carcass or protein) of the beef sub-system were slightly lower than the baseline and followed the same trend as total $CO_2eq\cdot year^{-1}$ emissions (Table 30, Figure 17).

Considering the food production from the whole-system, less external feed inputs were required due to lower number of animals to feed, more barley grain and straw were sold and less grain was required for animal feeding, increasing the overall return of human-edible food (Table 29), compared with the baseline system. As a result of the lower stock:crop balance of the HillAxL24 system, emissions of CO_2eq per kg of carcass were similar to the baseline scenario. However, considering that the total productivity of the HillAxL24 farm was greater than the baseline (HillLUI24), total emissions per unit of protein produced on-farm (beef+crops) were 28 % lower than the baseline system (Table 31, Figure 18).

5.3.1.2 Emphasis on the lowland area

As expected, the non-utilization of part of the available hill vegetation (i.e. more emphasis in the lower ground, LowlandLUI24) resulted in a reduction of the total number of stock reared on farm (Table 27) and the increment of the stock:crop balance (Table 28). More land and fertiliser were required for inbye grazing, and less for grass silage and total barley production, compared with the baseline system (Table 28). The number of cattle was constrained by the land available for inbye grazing and farm produced forage. As a result of less stock numbers, the overall productivity of the beef sub-system was reduced by 21%, compared with the baseline system (Table 29).

As a result of fewer animals on-farm, total CO_2eq emissions from the beef sub-system of the LowlandLUI24 were lower than the baseline system, but higher when compared on a herd basis. Due to the lower productivity of this simulated system but with fewer cattle, emissions per unit of product were slightly higher (4% more) than those estimated for the baseline system (Table 30, Figure 17).

Looking at the whole-farm, less spare land was available for cropping (Table 28). However, the use of external inputs were also reduced as a result of fewer finishing stock, hence returns of edible food were 0.3 t greater than the baseline system (Table 29). Total CO_2eq emissions were lower to the baseline system as a result of less enteric CH_4, less CH_4 and N_2O from manure management, less N_2O from crop residues, less CO_2 from diesel and embedded emissions (Figure 19). Although reduced numbers of cattle in the hill was associated with less productivity of the whole-farm (Table 29) this scenario was less dependent of external inputs and had lower overall emissions, which resulted in similar CO_2eq emissions per kilogram of total protein for human-consumption produced on-farm (Table 31, Figure 18).

5.3.1.3 Shorter finishing periods

Compared with the baseline system, finishing young cattle sooner (HillLUI14) resulted in a reduced stock:crop land use balance with fewer stock and more land used for cropping (Table 28). Similar numbers of breeding cows were possible to be kept on-farm as they were constrained by the use of the hill area for summer grazing (Table 26). Short duration finishing systems involved faster growth rates but lower slaughter weights and, if there is no opportunity to increase the size of the herd as assumed in this simulation, this resulted in a 14% reduction of the carcass production of the HillLUI14 system, compared with the baseline. However, in this modelling exercise, the reduction in carcass productivity of the farm was counteracted by the greater area for grain production (Table 29). Although greater amounts of barley grain were required for indoor feeding of individual cattle (Table 28), the total amount of external feed inputs were 6% lower than the baseline. The much larger overall protein productivity increased considerably (almost 20 times) the returns of human-edible food from the HillLUI14 system (Table 29).

Annually, total CO_2eq emissions from the beef sub-system per year, herd, carcass and protein from meat were lower than the baseline system (Table 30, Figure 17), as a result of less use of fertilisers, less imported feeds, less diesel and less external inputs for the beef sub-system (Figure 19).

When considering the whole-system, although more fertiliser was used for crop production due to more land designated for grain for feeding and saleable (Table 28), total emissions per year and per herd were lower for the HillLUI14 than the baseline system (Table 31). With slightly less meat production as a result of same number of animals (Table 27) sold at a lower BW (Table 26), total emissions of the system per kg of carcass were similar to the baseline. However, with much higher crop production, CO_2eq emissions per unit of total human-edible protein produced on-farm were 59% lower (27 kg CO_2eq.kg protein^{-1}.year^{-1} less) for HillLUI14 compared with baseline system (Table 31, Figure 18).

The main reasons for this emission reduction of the whole-farm (t CO_2eq.year^{-1}) were the lower emissions of enteric CH_4, and CH_4 and N_2O emissions from manure (Figure 20) as a result of less total animals on farm (Table 27).

5.3.2 Additive effect of management options

5.3.2.1 Efficient genotype and intensive use of the lowland

Compared with the baseline system (HillLUI24), the use of AxL together with higher concentration of stock on the lowland (i.e. higher stock:crop balance, LowlandAxL24 farm), negatively affected the carcass and grain productivity of the system (Table 29). Although, with lower human-edible inputs for cattle feeding required by LowlandAxL24, combining the use of more efficient genotype and intensive use of the lowland, resulted in an increment of returns of human-edible food by 0.8 t/DP; 89% more than the baseline system (Table 29). Comparing systems with low stocking rate in the hill and different genotypes, returns of human-edible food were higher for systems based on AxL cattle as a result of their higher carcass and crops production and similar use of human-edible inputs (Table 29).

In terms of GHG emissions, reducing the number of cattle in the hill (or intensive use of the lowland), together with using a more efficient breed did not have an important effect on both emissions per kilograms of carcass from the beef sub-system (Table 30, Figure 17) and emissions per unit of total protein products from the whole-farm, when compared with baseline scenario (Table 31, Figure 18).

5.3.2.2 Finishing period, lowland use and cattle genotype

Compared with the baseline system, carcass production per year was reduced as a result of shorter finishing period by 4 t/year (Table 29). Focusing grazing cattle on the lowland section of the farm together with shorter finishing periods (LowlandLUI14) did not have a negative impact on the carcass production of the systems. Nevertheless, combining these 2 management options increased the stock:crop balance of the farms with either LUI or AxL cattle, decreasing their crop production to the lowest values (48 and 45% less than the baseline system, respectively; Table 29). For these systems, human-edible inputs were high producing large negative figures of returns of human-edible food as a result of their heavy dependence on inputs and less land designated for crop production (Table 29).

In terms of GHG emissions, hill based systems with short finishing period (14 months) produced lower CO_2eq emissions both, in total and per herd (27% lower), and per unit of carcass from the beef sub-system (14% lower), compared with those using a longer time to finish the young stock (24 months; Table 30, Figure 17). For scenarios with either short or long finishing, an interaction can be observed of the effect of hill use and genotype on total emissions per year from the beef sub-system (Table 30, Figure 17). This interaction could be related to the carcass productivity of the systems, as it was cancelled out when expressing total emissions per kg of carcass (Table 30, Figure 17).

Looking at the whole-farm emissions (Table 31), systems with short finishing produced both the highest and lowest emissions per unit of total protein produced on-farm compared with the alternative systems. The highest whole-farm emissions per unit of total protein were observed for systems with short finishing, grazing focused upon the lowland sector of the farm and LUI cattle (LowlandLUI14; 29% higher than the baseline; Table 31, Figure 18). This was as a result of similar inputs (Table 28) and lowest productivity of beef and crop (Table 29), compared with the baseline. The lowest emissions per unit of product were observed for systems using short finishing, AxL cattle but with high use of the hill (Hill14 systems; 62% lower than the baseline; Table 31, Figure 18). These systems had more crop production in the lower ground allowing more productivity of the whole-system and the highest return of food for human consumption (Table 29). Systems with greater use of the hill but with long cattle finishing periods (Hill24) did not have the opportunity to produce as much saleable barley as the Hill14 systems as more inbye land was designated for grazing and silage production, thus figures of returns of edible food production were much lower for Hill24 than Hill14 systems.

Table 28. Body weight and body weight change of each category of animals in a herd of 2 cattle genotypes (Aberdeen Angus cross Limousin, AxL. vs. Luing, LUI) with intensive use of the Hill or Lowland. Finishing animals (males and females) had different BW and performance when in short (14 months old) and long (24 months old) finishing periods.

Intensive use	**Hill**				**Lowland**			
Finishing	**24**		**14**		**24**		**14**	
Genotype	**LUI**	**AxL**	**LUI**	**AxL**	**LUI**	**AxL**	**LUI**	**AxL**
Body weight, kg								
Cows	594	653	594	653	596	689	596	689
Cull cows	582	635	582	635	574	657	574	657
Weaned calves	179	211	179	211	201	222	201	222
Bulls	898	1098	898	1098	998	1198	998	1198
Slaughter weight								
Females	640	640	500	520	640	640	500	520
Males	640	640	500	520	640	640	500	520
Replacement heifers								
12-24 mo	386	423	386	423	390	441	390	441
24-36 mo	497	541	497	541	499	574	499	574
Body Weight Change, kg/d								
Cows	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bulls	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Females	0.465	0.450	0.892	0.858	0.448	0.454	0.829	0.829
Males	0.465	0.450	1.338	1.289	0.448	0.454	1.244	1.244
Replacement heifers								
12-24 mo	0.494	0.530	0.494	0.530	0.470	0.606	0.470	0.606
24-36 mo	0.369	0.400	0.369	0.400	0.375	0.450	0.375	0.450

Table 29. Total number of animals of each category (after mortality) of the baseline and alternative scenarios.

Intensive use	**Hill**				**Lowland**			
Finishing	**24**		**14**		**24**		**14**	
Genotype	**LUI**	**AxL**	**LUI**	**AxL**	**LUI**	**AxL**	**LUI**	**AxL**
Total dams	100	96	100	96	77	78	118	113
Cows	80	77	80	77	61	62	94	91
Cull cows	19	18	19	18	15	15	23	22
Calves	88	85	88	85	69	70	106	101
Finishing and over-wintering stock								
Females 12 mo	22	21	22	21	17	18	27	26
Females 24 mo	21	20	0	0	17	17	0	0
Males 12 mo	42	40	42	40	33	33	50	48
Males 24 mo	40	39	0	0	31	32	0	0
Replacement heifers								
12-24 mo	20	19	20	19	15	16	24	23
24-36 mo	20	19	20	19	15	15	23	22
Total stock[1]	265	256	205	197	206	210	243	234

[1]Not considering calves at foot. Two bulls were used for AI and afterwards mating (one for cows and one for heifers)

Table 30. Land use, on-farm organic fertiliser and external inputs to the baseline and alternative scenarios required as input data by the SAC C-calculator to predict total CO_2 equivalents of their related GHG emissions.

Intensive use	Hill				Lowland			
Finishing	24		14		24		14	
Genotype	LUI	AxL	LUI	AxL	LUI	AxL	LUI	AxL
Land use, ha								
Total	338	338	338	338	338	338	338	338
Hill	269	269	269	269	269	269	269	269
Inbye grazing	17	14	9	8	28	28	34	34
Grass silage	20	19	8	8	16	16	10	11
Total barley	32	37	52	53	25	25	25	25
Area for sold grain/straw								
Crop sold, ha	15	22	37	40	12	12	8	8
Stock:crop ratio	21	15	8	8	27	27	42	40
Organic Fertiliser (FYM), tonnes								
Inbye grazing	59.8	45.8	20.1	17.3	78.3	78.3	90.8	88.9
Grass silage	71.9	61.3	18.6	18.1	43.7	43.8	26.5	27.9
Barley	112.6	122.1	117.1	114.5	68.8	70.2	68.0	64.9
Total	244.3	229.2	155.8	149.9	190.8	192.3	185.2	181.8
Inorganic Fertiliser, tonnes								
Inbye grazing	4.1	3.3	2.2	1.9	6.9	6.8	8.2	8.2
Grass silage	5.0	4.5	2.0	2.1	3.9	3.9	2.4	2.6
Barley	5.6	6.5	9.2	9.4	4.4	4.4	4.5	4.4
Total	14.7	14.4	13.4	13.4	15.2	15.2	15.1	15.2
Feed, bedding and sold, total t DM/year								
Grass silage	144	131	58	59	112	112	70	75
Barley silage	126	115	51	52	98	98	61	66
Barley grain sold	113	162	278	296	89	92	59	62
Barley grain fed	54	49	83	71	42	42	97	86
Barley straw sold	0	37	172	181	0	0	0	0
Straw fed, bedded	125	121	98	93	98	100	116	110
Imported feeds, t DM/year								
Maize dark grain	36.1	32.8	32.1	28.8	28.1	27.9	37.7	35.4
Minerals	7.2	6.6	4.7	4.7	5.6	5.6	5.5	5.4
Molasses	0	0	1.8	1.4	0	0	2.0	1.7
Diesel use, 1000 litres								
Beef	6.93	6.39	4.52	4.27	5.71	5.72	5.82	5.70
Grain/straw sold	1.81	2.59	4.45	4.74	1.42	1.47	0.94	0.99
Total	8.75	8.99	8.97	9.01	7.14	7.19	6.76	6.69

Table 31. Inputs, outputs and return of human digestible protein generated by the baseline and alternative scenarios

Intensive use	Hill				Lowland			
Finishing	24		14		24		14	
Genotype	LUI	AxL	LUI	AxL	LUI	AxL	LUI	AxL
Human-edible inputs								
Barley grain, t DM	126	115	112	101	98	98	132	124
Maize dark grain, t DM	36	33	32	29	28	28	38	35
Molasses, t DM	0	0	4.7	1.4	0	0	2.0	1.7
Total input, t DP/year[1]	17	15	16	14	13	13	18	17
Human-edible outputs								
Products, t/year								
Carcass	29	29	25	25	23	24	30	31
Barley grain	113	162	278	296	89	92	59	62
Protein, t DP/year								
Meat	3.7	3.7	3.2	3.2	2.9	3.0	3.8	3.9
Barley	12.3	17.6	30.2	32.1	9.6	10.0	6.4	6.7
Total	16.0	21.2	33.3	35.3	12.5	13.0	10.2	10.6
Human-edible returns								
Output-input, t DP/year	-0.9	5.9	17.8	21.7	-0.6	-0.1	-7.7	-6.1

[1]DP = human digestible protein, estimated with DP content of inputs and outputs as mentioned in Table 25.

Table 32. Emissions of CO_2 equivalents from baseline and alternative scenarios. Total emissions, emissions per herd, carcass or total protein produced from the beef sub-system only.

Intensive use	**Hill**				**Lowland**			
Finishing	**24**		**14**		**24**		**14**	
Genotype	**LUI**	**AxL**	**LUI**	**AxL**	**LUI**	**AxL**	**LUI**	**AxL**
t CO_2eq.year^{-1}								
CH_4	364	349	282	277	259	267	298	300
N_2O	202	182	149	141	176	177	207	207
CO_2	124	110	75	70	124	124	133	132
Total	690	640	506	488	559	567	638	638
t CO_2eq.100 cows^{-1}.year^{-1}								
CH_4	365	363	282	288	338	342	253	265
N_2O	203	189	149	147	231	227	175	183
CO_2	125	114	75	72	162	158	113	116
Total	693	665	506	507	731	727	541	563
kg CO_2eq.kg carcass^{-1}.year^{-1}								
CH_4	12.4	12.1	11.3	10.9	11.3	11.1	10.0	9.8
N_2O	6.9	6.3	6.0	5.6	7.7	7.4	6.9	6.8
CO_2	4.2	3.8	3.0	2.7	5.4	5.2	4.4	4.3
Total	23.6	22.2	20.2	19.2	24.5	23.7	21.3	20.8
kg CO_2eq.kg Protein from meat^{-1}.year^{-1}								
CH_4	98	95	89	86	89	87	78	77
N_2O	54	50	47	44	61	58	54	53
CO_2	33	30	24	22	43	41	35	34
Total	186	175	159	151	193	186	167	164

Table 33 Emissions of CO_2 equivalents from baseline and alternative scenarios. Total emissions, emissions per herd, carcass or total protein produced from the whole-farm system, considering beef and crop production.

Intensive use	Hill				Lowland			
Finishing	24		14		24		14	
Genotype	LUI	AxL	LUI	AxL	LUI	AxL	LUI	AxL
t CO_2eq.year^{-1}								
CH_4	364	349	282	277	259	267	298	300
N_2O	222	212	202	197	192	193	216	216
CO_2	145	143	136	134	141	141	143	142
Total	731	703	620	608	592	600	657	658
t CO_2eq.100 cows^{-1}.year^{-1}								
CH_4	365	363	282	288	338	342	253	265
N_2O	223	220	202	205	251	247	183	191
CO_2	146	148	136	139	184	180	121	126
Total	734	731	620	632	773	769	557	581
kg CO_2eq.kg carcass^{-1}.year^{-1}								
CH_4	12.4	12.1	11.3	10.9	11.3	11.1	11.3	10.9
N_2O	7.6	7.4	8.1	7.8	8.4	8.0	7.2	7.1
CO_2	5.0	5.0	5.4	5.3	6.2	5.9	4.8	4.6
Total	25.0	24.4	24.8	24.0	25.9	25.0	21.9	21.5
kg CO_2eq.kg total protein^{-1}.year$^{-1(1)}$								
CH_4	22.8	16.4	8.5	7.8	20.6	20.5	29.3	28.3
N_2O	13.9	10.0	6.0	5.6	15.3	14.8	21.2	20.4
CO_2	9.1	6.7	4.1	3.8	11.2	10.8	14.0	13.4
Total	45.8	33.1	18.6	17.2	47.2	46.2	64.6	62.1

[1]Total CO_2eq. emissions per kg of total protein produced on farm including protein from meat and grain products.

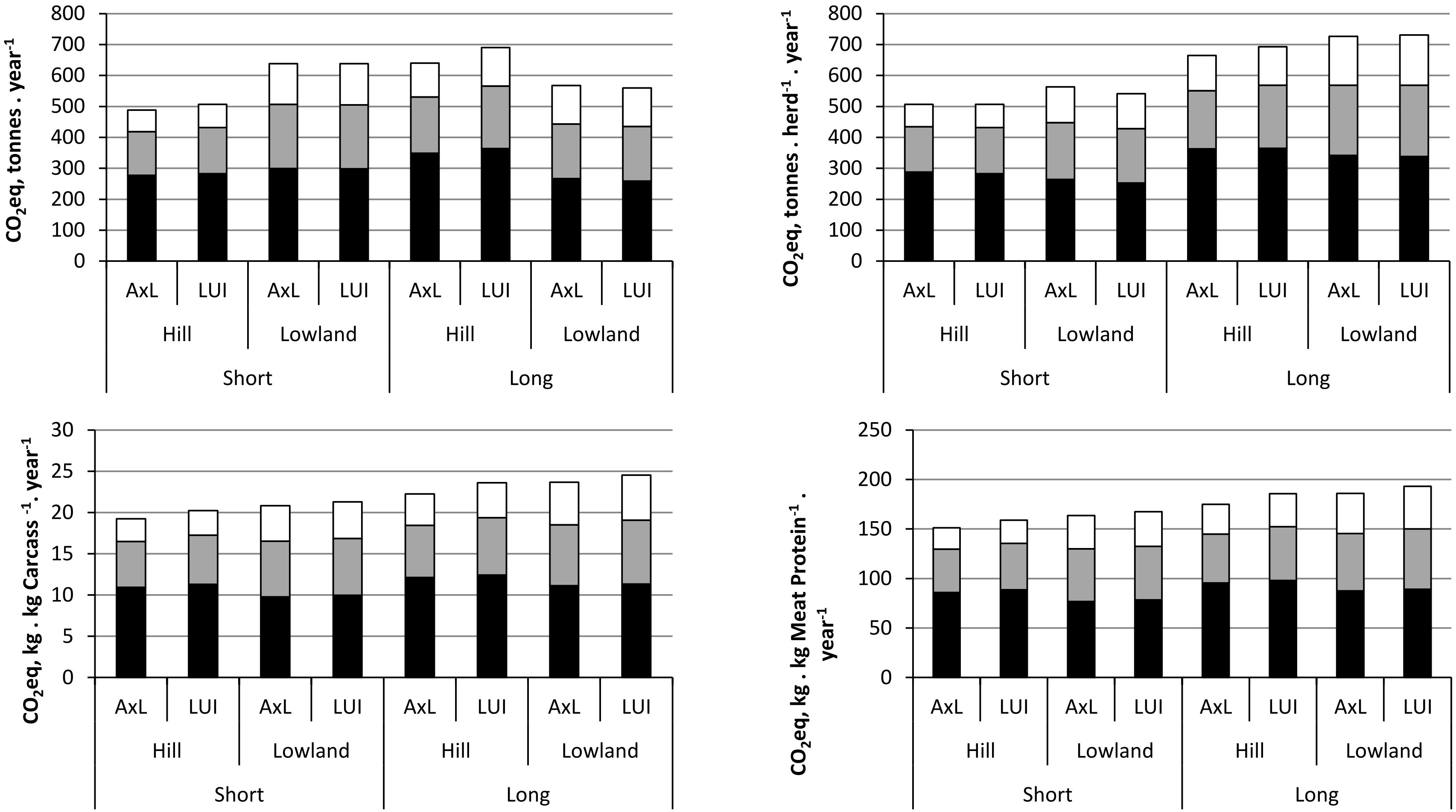


Figure 17. Total emissions of CO_2eq. from CH_4 (black), N_2O (grey) and CO_2 (white) of the beef sub-system only.

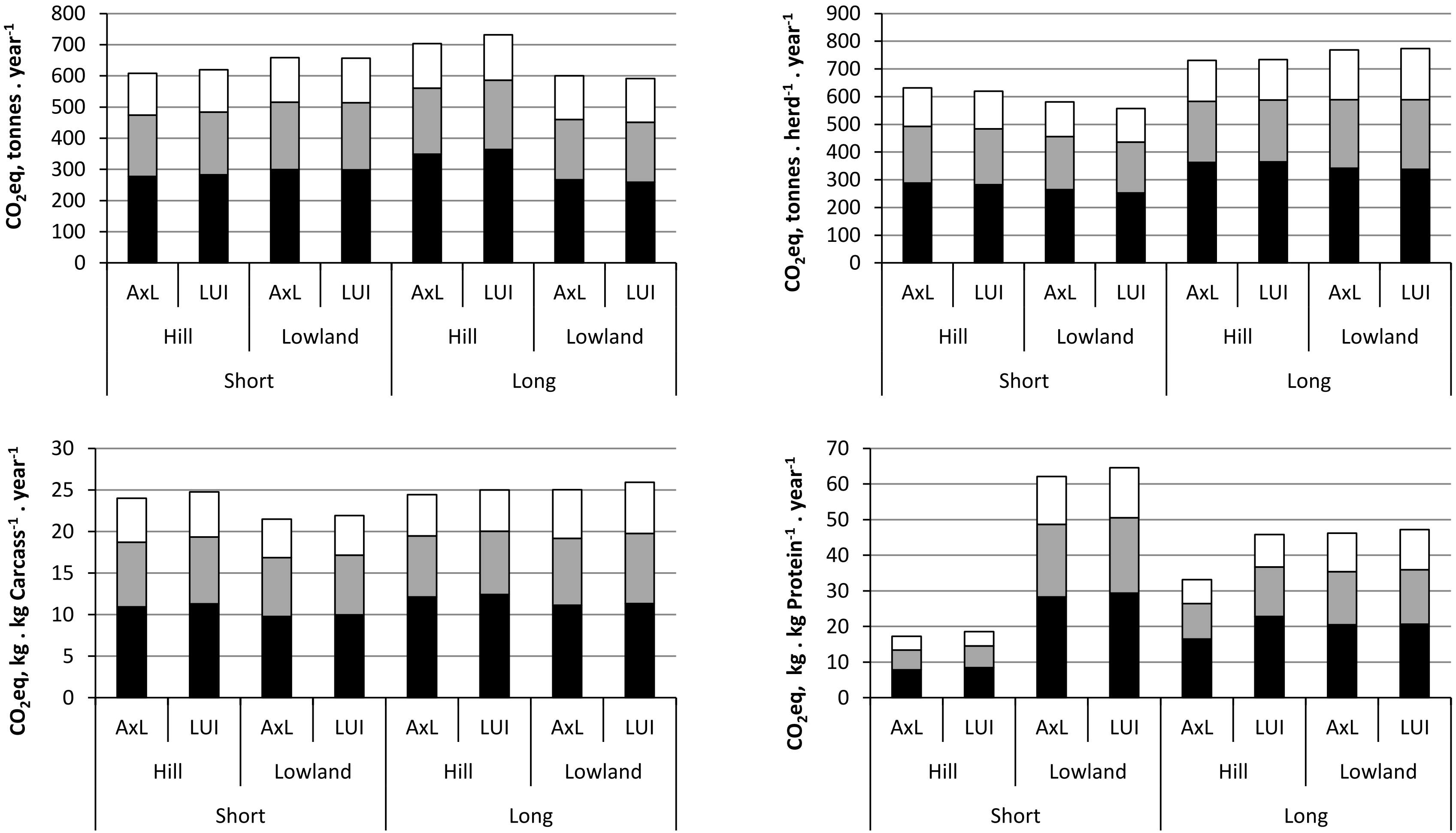


Figure 18. Total emissions of CO_2eq. from CH_4 (black), N_2O (grey) and CO_2 (white) of the whole-farm, considering emissions and production from the beef and crop production.

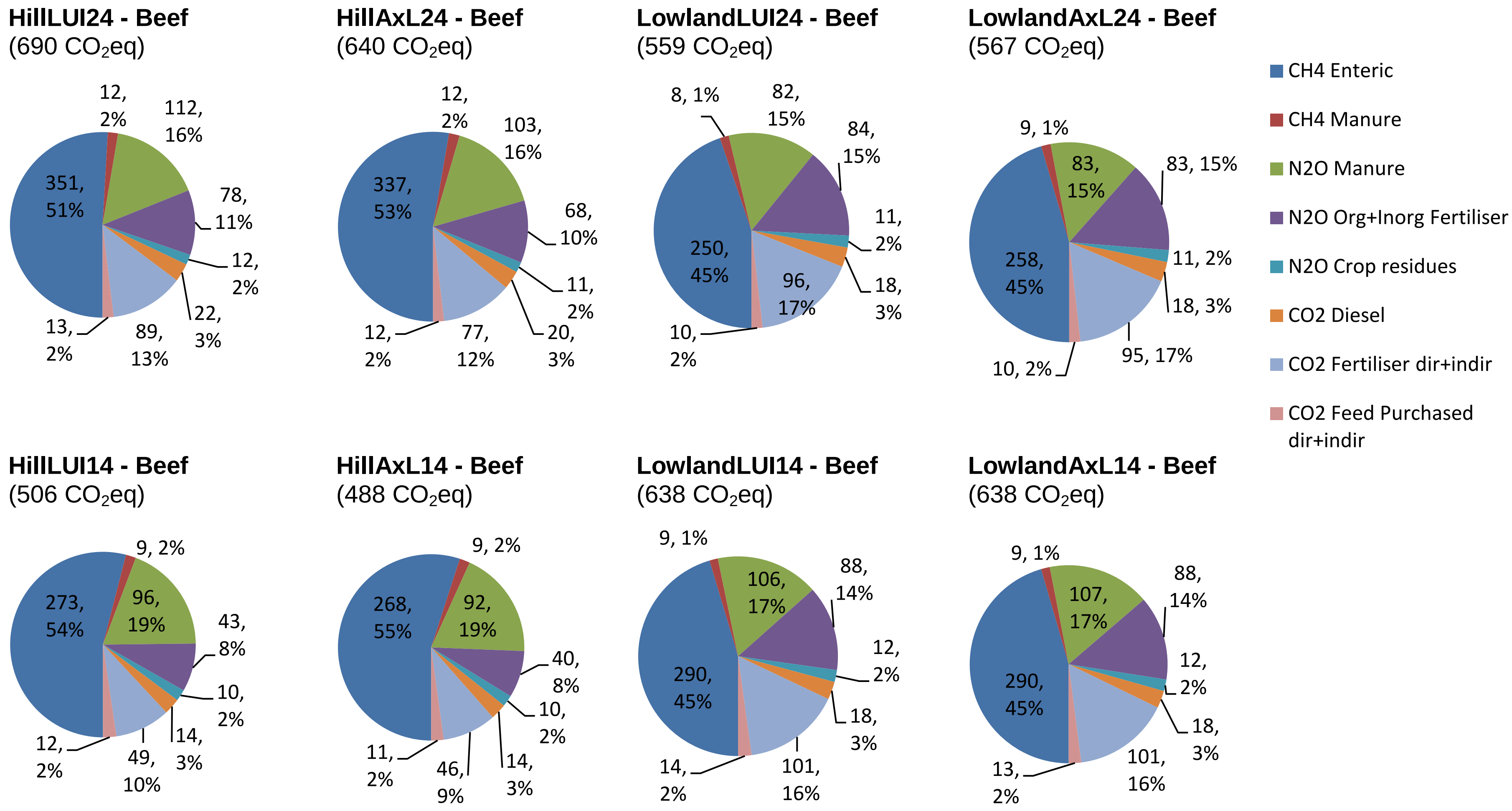


Figure 19. Total carbon dioxide equivalent emissions (CO_2eq, t/year) from the baseline and alternative systems, and CO_2eq. (t/year, percentage) from methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) from each of the sources of the beef sub-system only.

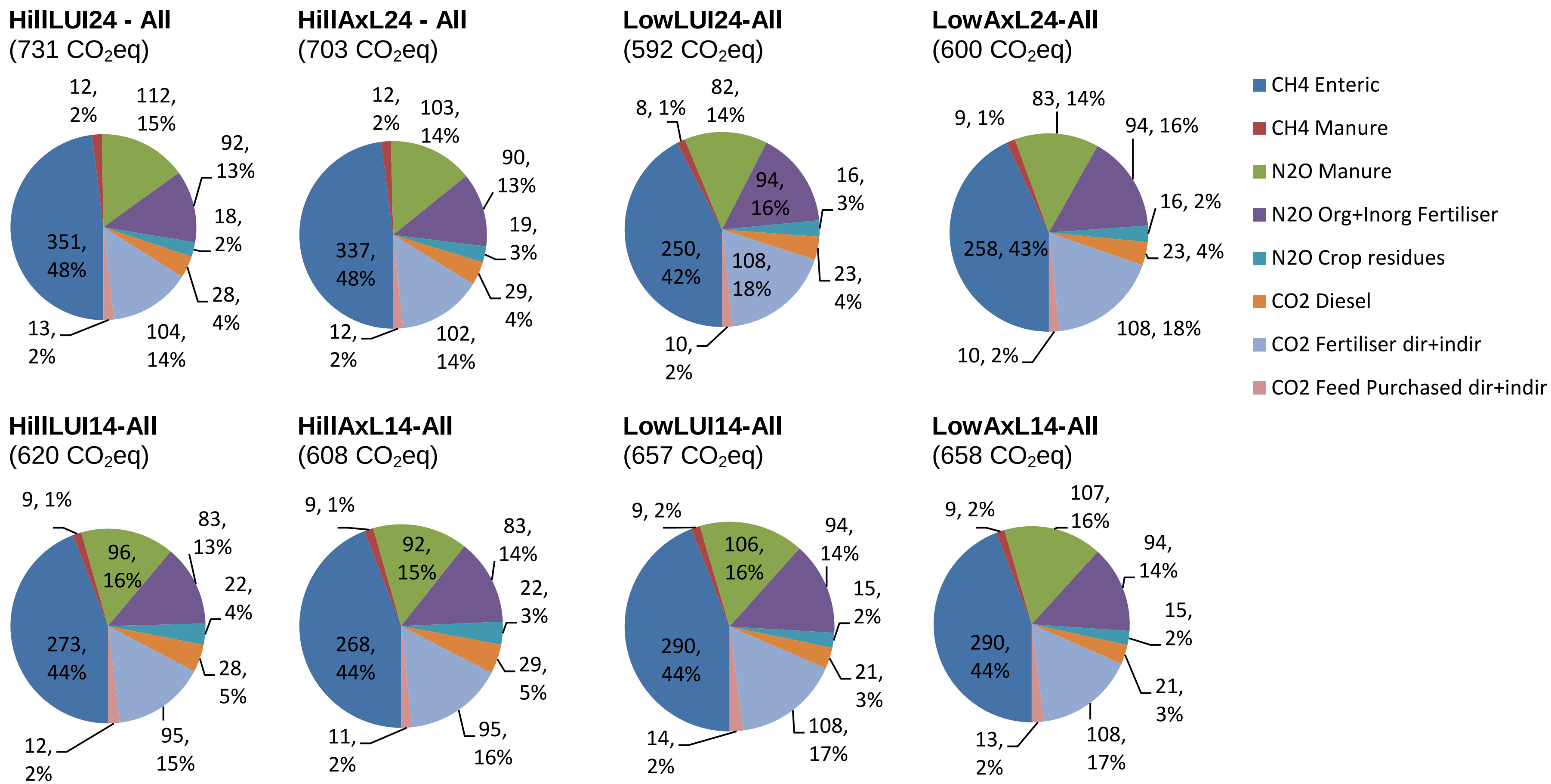


Figure 20. Total carbon dioxide equivalent emissions (CO_2eq, t/year, percentage) from methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) from each of the sources of the whole-farm, considering beef and crop production.

5.3.3 Uncertainty analysis

As was shown in the previous sections, the adoption of alternative management affected both total GHG emissions and productivity of the farms. Thus, total CO_2eq emissions per unit of product reflect the effect on final outcomes of some of the interactions between carbon footprint reduction and productivity improvement as a result of the application of different management. However, there are important sources of uncertainties involved on the prediction of GHG emissions and farm productivity. Therefore, an uncertainty analysis was performed on total CO_2eq emissions per unit of total protein produced on-farm to further analyse the probability of occurrence of the results observed in the previous sections.

Including uncertainty ranges for the DMD of the grasslands, cattle performance and GHG emission factors as described in Table 24, a large variation of CO_2eq emissions per unit of total protein produced by the farms was observed, as shown in Figure 21. This graph shows the cumulative probability function (**CPF**) of CO_2eq emissions (kg CO_2eq.kg protein^{-1}.year^{-1}) for the different farming systems. Systems located towards the right side had higher emissions than those at the left, while wider CPF depicts more uncertain results than narrower ones. Hill based systems with short finishing period appeared to be more robust (i.e. less uncertain) with lower ranges of uncertainty for their resulting emissions, as observed by their narrower CPF (Figure 21), narrow range of results and smaller SD (Table 32). By contrast, the least robust were observed to be lowland based systems with short finishing period (Figure 21) with the highest standard deviations and wider range of results (Table 32). For lowland based systems, the variation assumed in emission factors contributed a large proportion to the overall uncertainty observed in these systems (Table 32). The stock:crop balance was most variable (max-min, Table 32) in lowland short finishing systems, which could have contributed to the larger uncertainty observed for these systems.

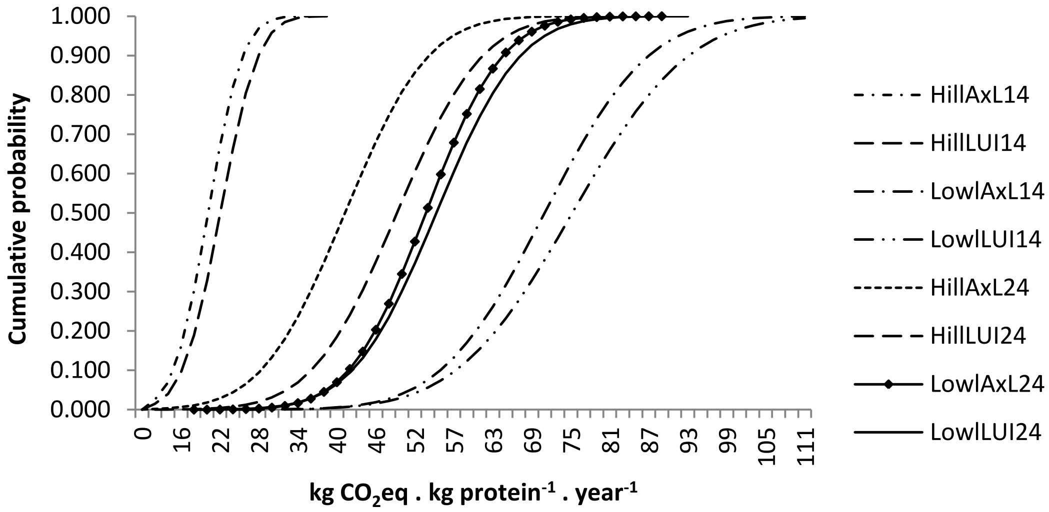


Figure 21. Cumulative probability of total greenhouse gas emissions per unit of product produced on-farm (kg CO_2eq·kg protein^{-1}·year^{-1}) for the alternative management options considering variation on dry matter digestibility of grasslands, cattle performance and emission factors as described in Table 24.

Table 34. Statistics from the Monte Carlo simulation of the total CO_2eq emissions per unit of product of alternative systems, proportional contribution to uncertainty of emission factors and variation in dry matter digestibility and cattle performance and ranges of total emissions, products and returns observed when considering upper and lower uncertainty values.

Intensive use	**Hill**				**Lowland**			
Finishing	**24**		**14**		**24**		**14**	
Genotype	**LUI**	**AxL**	**LUI**	**AxL**	**LUI**	**AxL**	**LUI**	**AxL**
CO_2eq, kg.kg protein-^{1}.year^{-1}								
Mean[1]	48.9	41.0	22.1	20.3	54.8	53.2	75.4	71.2
Min	26.8	21.2	13.0	12.2	35.7	35.5	48.3	47.2
Max	74.5	67.0	33.6	30.5	80.7	77.0	110.6	103.7
Range	47.6	45.8	20.7	18.3	45.0	41.5	62.2	56.5
Standard deviation	10.14	9.93	4.52	4.10	9.95	9.11	13.75	12.32
Contribution to Standard deviation, %[2]								
Emission Factors	66	56	72	76	88	90	80	83
DMD and performance	34	44	28	24	12	10	20	17
Total CO_2eq, tonnes.year^{-1}								
Min	547	526	461	453	456	463	509	510
Max	1132	1157	1040	1024	989	1000	1068	1070
Range	584	630	578	570	533	537	559	560
Protein production, tonnes.year^{-1}								
Min	20.8	25.1	36.0	37.4	12.8	13.2	10.7	10.9
Max	15.0	16.9	30.3	33.0	12.1	12.7	9.5	10.2
Range	5.8	8.2	5.7	4.4	0.7	0.5	1.2	0.7
Human-edible returns, tonnes DP.year^{-1}								
Min	6.7	12.0	23.1	25.8	0.9	1.2	-5.1	-4.1
Max	-3.1	-1.1	11.7	17.0	-2.2	-1.5	-10.6	-8.4
Range	9.8	13.1	11.4	8.8	3.1	2.7	5.5	4.3
Stock:crop balance								
Min	23.6	20.6	9.3	8.4	29.3	28.0	50.5	45.4
Max	14.6	11.5	7.3	6.9	26.2	25.5	37.2	36.4
Range	9.0	9.1	2.0	1.5	3.2	2.5	13.3	9.0

[1]Results from simulation considering variation in emission factors, DMD and performance.
[2]Estimated from 2 separate simulations considering variation in either emission factors only or DMD and performance only.

5.3.4 Alternative strategies

After comparing a series of alternative management options represented in the form of farming ***systems***, further technologies available to mitigate GHG emissions were subsequently included to each of the systems to represent alternative ***strategies***. These alternative strategies are compared relative to the baseline strategy which uses pure grass lowland pasture, current genotype, high level of fertilizer and no dietary additives. Changing the strategy of management impacted on the systems components as well as on the final productivity and carbon footprints. Thus, extra-information is provided in an Appendix where more detailed data is given.

5.3.4.1 Effect of mitigation options on total CO_2eq emissions

The use of dietary additives, which reduced emissions of individual animals receiving the additive by 20%, reduced total CO_2eq emissions from the whole farm and per herd by up to 4.5% (Figure 22). However, this effect interacted with other technologies applied on the farm. This interaction had a different magnitude depending on the type of farm or management previously adopted. For instance, reductions of up to 26% in total emissions per year were observed on the LowlandLUI24 system when combining the use of additives with grass/clover swards, less fertilizer and improved genotype, relative to the baseline strategy (Figure 22b). However, the same combination of technologies caused a reduction on total CO_2eq emissions of only 8% in the Hill14 systems (with either genotype) compared with the baseline situation (Figure 22b). The different responses observed on different systems as a result of applying the same technology (or a set of technologies) reflect the differing flexibility to adapt to the changes caused by the application of new management options of different systems. For instance, alternative management and technologies impacted on the total number of cattle on farm and the stock:crop land use balance, and these changes were of different magnitude depending on the characteristic of the systems (Figure 23).

After applying different GHG mitigation options, the results observed on CO_2eq emissions at the beef herd level have different trends compared with total emissions for the whole farm per year (Figure 22) as a result of different changes to the structure of the farm. Per unit of herd, emissions were lower for lowland based systems with short finishing of cattle (Lowland14), followed by hill short finishing based systems (Hill14), and systems with long finishing based either lowland or hill (Lowland24 or Hill24; Figure 22c). This distinction cannot be clearly seen when results are presented as total emissions per year (Figure 22a).

The relative impact of mitigation technologies varied when applied to different systems in terms of total CO_2eq emissions per herd (Figure 22c). This difference was more noticeable when comparing the use of grass/clover swards. This management option created a range of responses from the different managed systems, having a relative bigger reduction potential on lowland based systems with long finishing periods (Figure 22c).

The use of improved genotype also affected the number of cattle and stock:crop balance of the farm (Figure 23), as cattle of improved genotype were assumed to require 20% less energy for a similar level of performance, hence affecting emissions from the beef sub-system. The total number of cattle on-farm generally increased by using improved cattle genotype, but the magnitude of change was different depending on the system and type of management adopted previously (Figure 23b). For instance, hill systems using improved genotype had relatively high increments of stocking (Figure 23b). However, these systems had no reductions or, in some cases, small increment on stock:crop balance, resulting in a relative increase in total emissions of Hill14 systems using improved cattle genotype (Figure 22a and b). However, by scaling emissions to a 100 cow herd, it can be demonstrated that the increment on total emissions of hill based systems (of up-to 5% relative to the baseline scenario) was due to more animal numbers, as these systems had the highest relative reduction in emissions per herd (Figure 22d).

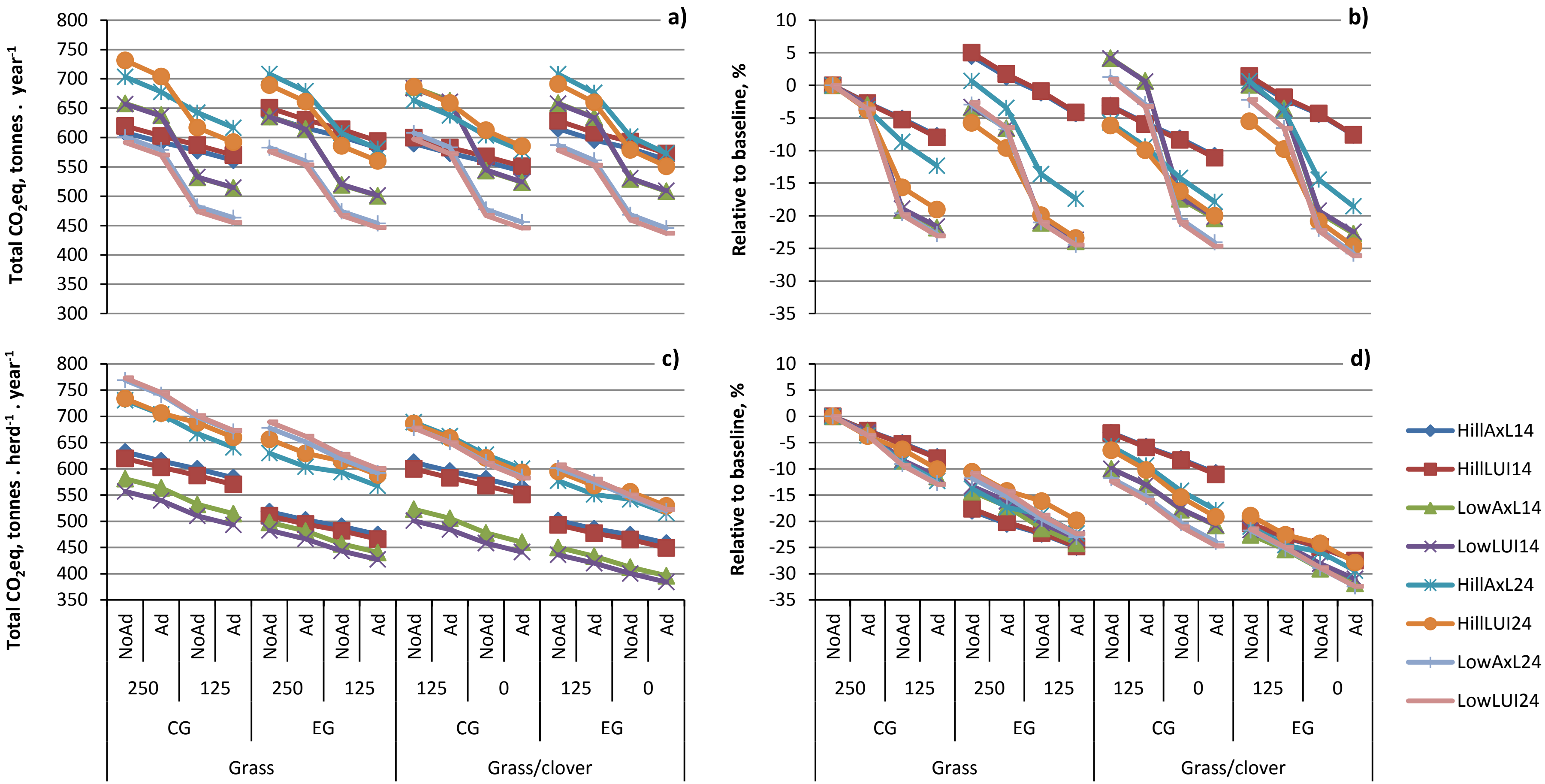


Figure 22. Relative effect of mitigation technologies on total CO_2eq emissions for the farm per year (a, b) and only for the beef herd (c, d) of alternative scenarios. Mitigation technologies described as Ad: dietary additives; 0, 125 and 250: levels of inorganic fertiliser; CG: current genotype; EG: efficient genotype (use of genetic improvement); Grass: pure grass or Grass/clover: mixed grass/legumes lowland pasture.

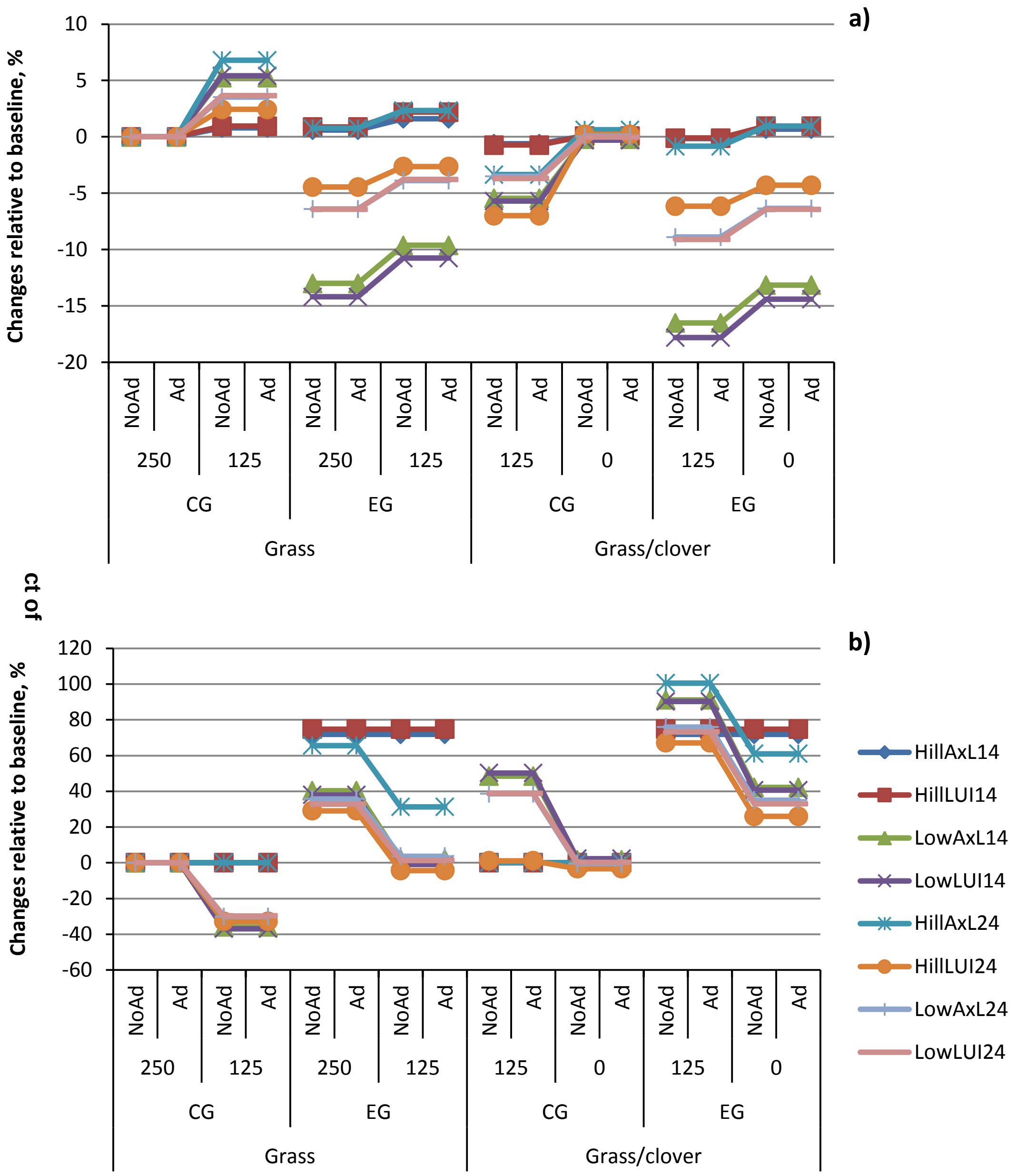


Figure 23. Changes relative to the baseline scenario (%) of GHG mitigation technologies on a) stock:crop balance and b) total number of cattle on farm of simulated systems. Mitigation technologies described as Ad: dietary additives; 0, 125 and 250: levels of inorganic fertiliser; CG: current genotype; EG: efficient genotype; Grass: pure grass or Grass/clover: mixed grass/legumes lowland pasture.

5.3.4.2 Effect of mitigation options on productivity and emissions per unit of product

5.3.4.2.1 Beef sub-system

Technologies applied for GHG mitigation had different impacts on the productivity of the systems (Figure 24a), with the exception of dietary additives as it was assumed these additives have neither impact on feed intake nor on performance of the animals. The use of lower fertilizer levels applied to the same type of sward reduced the productivity of the beef sub-system, with the exception of Hill14 systems and in some cases Hill24 systems. Hill based systems are less dependent on the lowland part of the farm (where fertilizer is applied) for forage production. Lowland based systems had to reduce their number of animals and increase their stock:crop balance (Figure 20) designating more land to grass and less to barley, as a result of lower fertilizer levels as this affects grass yields available for forage production. The use of an improved cattle genotype had a relative bigger impact on the productivity of Hill14 systems with pure grass swards (Figure 24b) than on the other systems.

When expressing emissions per unit of product (Figure 24c), changes in the order of the systems, ranked in terms of size of emission, can be observed compared with the total emissions per year (Figure 22a). The use of dietary additives had a relatively similar impact on all the systems under study (Figure 24c and d). However, more diverse responses on CO_2eq emissions per unit of product were observed among systems when varying the level of fertilizer and the type of sward. Overall, combining the use of additives, with low fertilizer, improved genotypes and grass/clover swards applied to lowland based systems with long finishing and LUI cattle (LowlandLUI24), showed the highest mitigation potential of GHG emissions per unit of product from the beef sub-system of up-to 76%, relative to the baseline strategy of management (no additives, high fertilizer, current genotype and pure grass).

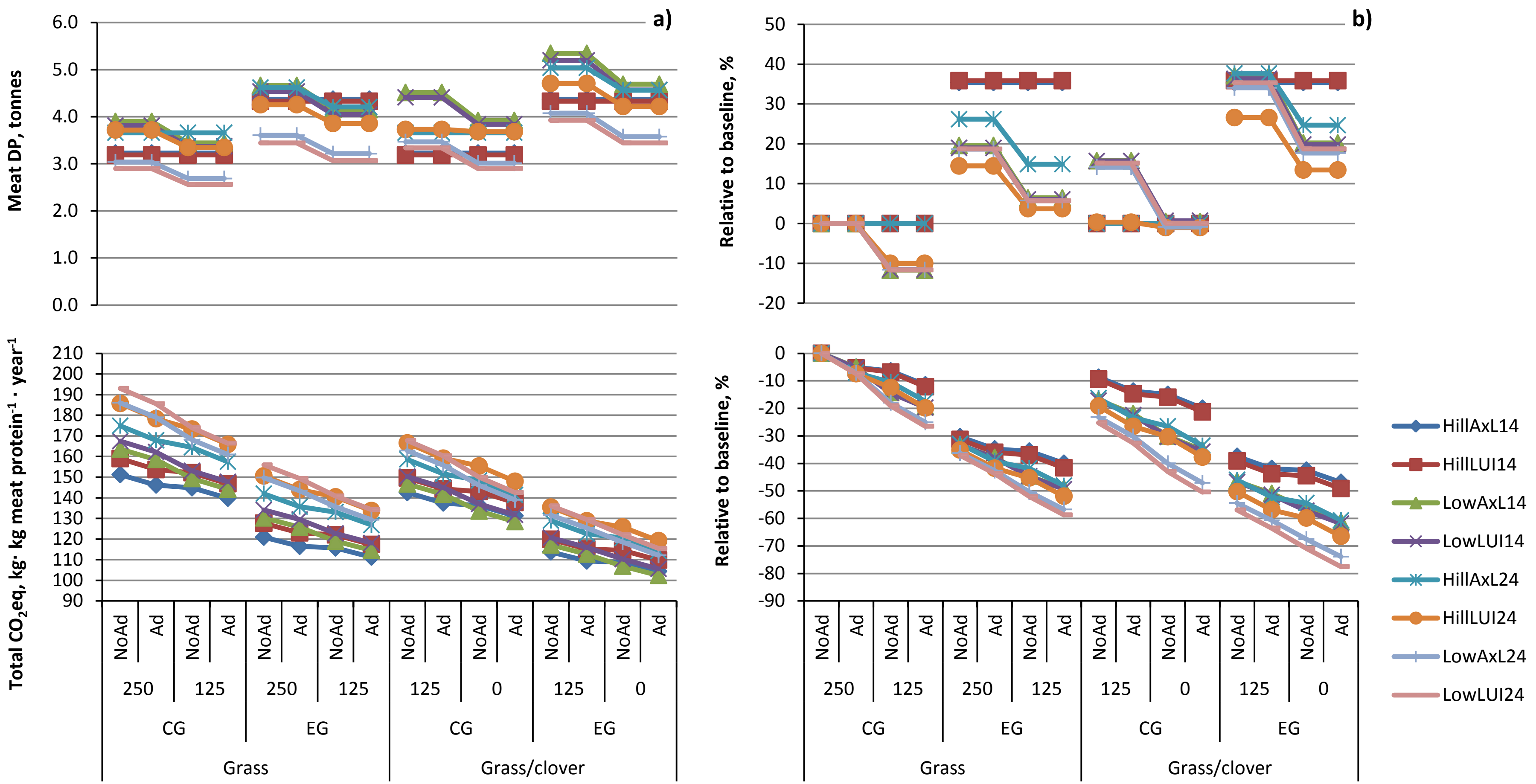


Figure 24. Effect of mitigation technologies on the productivity (a, b) and CO_2eq emissions (c, d) from the beef sub-system. Mitigation technologies described as Ad: dietary additives; 0, 125 and 250: levels of inorganic fertiliser; CG: current genotype; EG: efficient genotype; Grass: pure grass or Grass/clover: mixed grass/legumes lowland pasture.

5.3.4.2.2 Whole-farm system

As a result of the diverse management options applied to the baseline systems, the scenarios under study had different stock:crop land use balance which impacted on the total productivity of the farm, when considering beef and crop production together (Figure 22a). Although a bigger relative increment was observed on the total productivity of lowland based farms by using improved genotypes (Figure 22b), these changes were not enough to reach the level of productivity of total human-digestible protein (DP) of hill based farms (Figure 22a). This is as a result of the larger proportion of land designated to crop production which is less "carbon intensive" on the hill focused farms, compared with lowland farms (lower stock:crop balance). Total CO_2eq emissions from the whole-farm per unit of total DP product of lowland based systems were more affected in relative terms by the use of available technology than hill based systems (Figure 25c and d). Hill based systems that finish their young cattle soon (Hill14) have less opportunities for reducing their total emissions per unit of product when compared to lowland based systems and hill systems with long young stock finishing (Figure 25).

The response observed for total emissions per product from the whole-farm after reducing the level of fertilizer on some of the simulated systems (Hill24) was opposite the others (Figure 25c and d). As shown, different responses on productivity and carbon emissions were observed in different systems as a result of application of alternative mitigation options. Generally, total emissions of different systems were reduced as a result of less fertilizer application (Figure 22). However, at the same time this practice either increased or had no effect on total number of cattle on farm (Figure 23b) and tended to increase the stock:crop balance of different systems (Figure 23a). Less fertilizer reduced or did not affect meat production (Figure 24a) and generally reduced the overall whole-farm productivity of all simulated systems (Figure 25b). The different responses of the simulated systems under the same management practice reflect the different structure of the farms.

Looking at the total CO_2eq per total DP produced (Figure 25c and d), the question arises of why Hill24 based systems would respond in a different direction compared to other systems. The hill based systems with LUI cattle and long finishing periods

(HillLUI24) was designed as the baseline system and adjusted to maintain 100 cows herd of LUI cattle with minimum excess of barley (some grain surplus but zero straw surplus). Thus, under a situation of reduced grass yields as a result of less fertiliser application this HillLUI24 system had no flexibility to used spare land to adjust their demands. For that reason, this system has to reduce the number of animals (Figure 23b) as a result of reducing the amount of fertiliser.

A different response is observed with the HillAxL24 system when fertilizer strategies are compared. Differences between AxL and LUI systems with long finishing are explained by the assumptions made regarding the slaughter weights of finishing animals. On the contrary, similar slaughter weights (640 kg) were assumed for both genotypes finished at 24 months of age. Thus, demands for lowland forage and silage are higher for LUI than AxL cattle over the finishing period due to lighter weights of LUI cattle at weaning compared with AxL, both aiming for the same slaughter weight. In a system with high fertiliser as in the baseline strategy, AxL system can maintain fewer cows in the hill because of their bigger size, but the requirements of finishing cattle maintained in the lowland area are lower than LUI cattle. Therefore, the AxL system has spare land to produce extra barley grain and straw and which can be converted to grass after reducing the amount of fertiliser and maintain the same number of animals on farm. On the other hand, because the LUI system (baseline) did not had spare land for straw and barley after reducing fertiliser on grass the number of cattle needs to be reduced to produce the feed required for the finishing animals.

The total CO_2eq per total DP produced of HillAxL24 system increased after reducing fertiliser at a different magnitude to that HillLUI24 (Figure 22c and d). As explained before, under a situation of reduced grass yield as a result of less fertiliser, AxL systems extended the land designated to grass at the expense of crop production. Thus, under the same strategy of reduced fertiliser, HillLUI24 system reduced the number of animals but did not compromise crop production, whereas HillAxL24 maintained number of animals and reduced crop productivity. This reduction in crop production reduced by a bigger magnitude the overall DP productivity of AxL compared to LUI farms (Figure 25a and b). Therefore, in these cases, the reduction of productivity of the Hill24 systems (from 10 to 25%; Figure 25b) was more important than reduction of total emissions (from 9 to 16%; Figure 22d). This response has caused either an increment or less reduction of emissions per unit of product of the whole-farm in most of the hill based systems (Figure 25c and d).

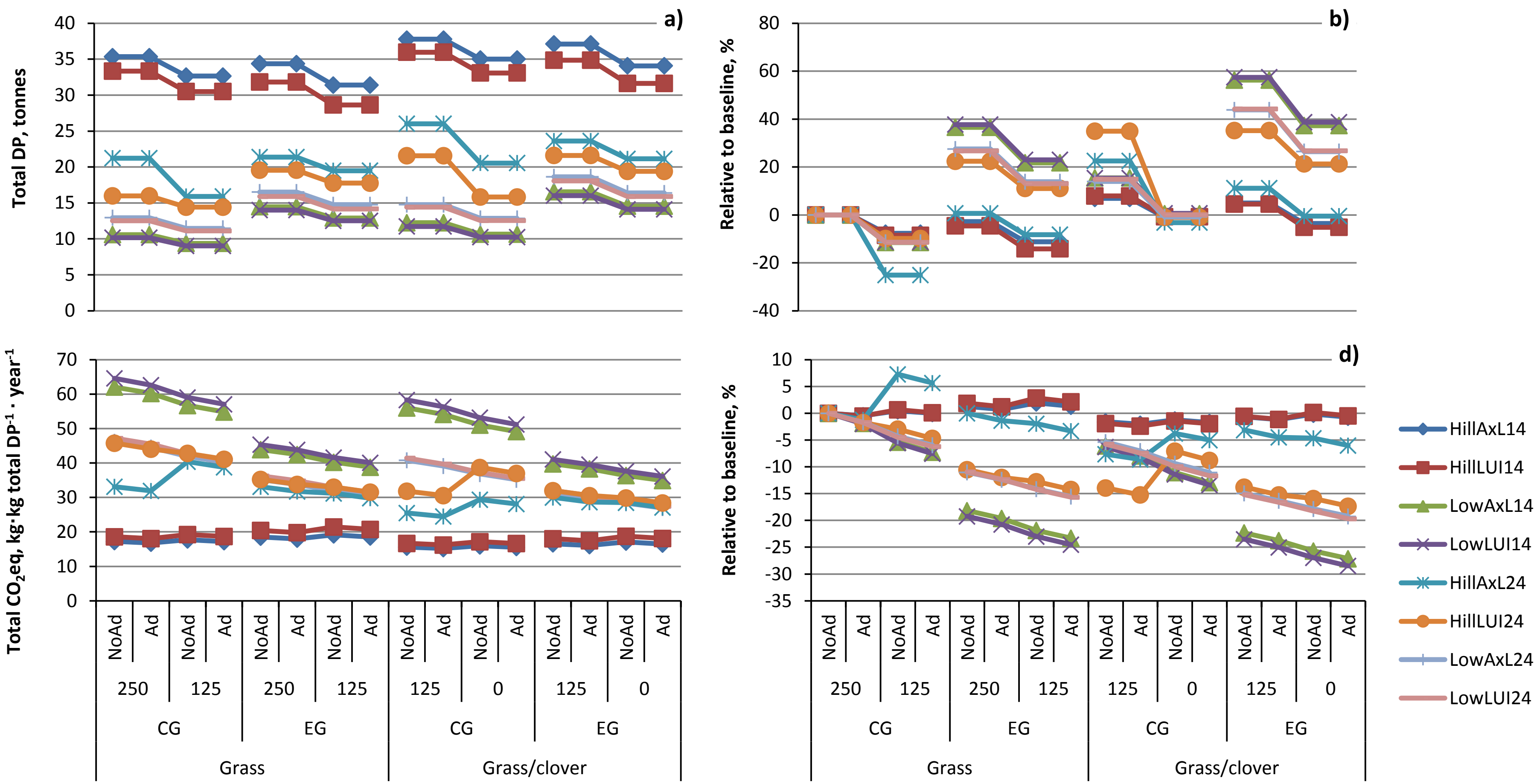


Figure 25. Effect of mitigation technologies on the productivity (a, b) and CO_2eq emissions (c, d) from the whole-farm system. Mitigation technologies described as Ad: dietary additives; 0, 125 and 250: levels of inorganic fertiliser; CG: current genotype; EG: efficient genotype; Grass: pure grass or Grass/clover: mixed grass/legumes lowland pasture.

Greenhouse gas emissions from contrasting beef production systems

5.4 Discussion

Many GHG mitigation studies have looked at a single factor effect when studying management alternatives. Some examples are studies comparing strategies to reduce emissions from beef suckler-cows (Casey and Holden, 2006), beef finishing (Pelletier et al., 2010), breeding-finishing beef (White et al., 2010), and dairy (Yan et al., 2013) systems. The study carried out in this chapter adds novelty compared with these previous studies by studying interactions between management alternatives. As far as I am aware such studies on interactions when combining mitigation options have not yet been mentioned in the literature. Moreover, some of these studies used a standard Life Cycle Assessment (LCA) methodology to study total GHG emissions of the systems. Differently, in this chapter I decided to use a bespoke model instead of the standard LCA methodology for the studying the effect of GHG mitigation alternatives in order 1) to introduce improvements on CH_4 prediction equations as reported in Chapter 2 of this thesis and 2) to allow different component of the system (e.g. number of hectares and animals) to interact as a result of combined application of alternative GHG mitigation management (e.g. finishing period length, fertiliser use).

Management options tested in this study were noted to have an important impact on reducing emissions from agriculture (MacLeod et al., 2010; Moran et al., 2011). However, conclusions obtained in these studies were obtained by assuming no changes on the components of the system and generalising mitigation potentials amongst farming characteristics which typically differ considerably. In contrast, results from this chapter have demonstrated the complexity of studying the application of alternative management options proposed to reduce GHG emissions under diverse circumstances, and that the relative importance of mitigation options differ between types of systems. Thus, aspects related with this complexity are further described below.

Mitigation policies have been proposed by many stakeholders and governments. For instance, it has been proposed that reducing the number of cattle rapidly reduces CO_2eq emissions from beef farming systems (Welsh Assembly Government, 2010).

However, this approach does not consider the problem of food production. Moreover, this study has shown that the response to this simple management option rather depends on the characteristic of the systems and in cases represented here reducing the number of cattle on the hill did not have the results previously hypothesised. For example, in the systems simulated for this study, the land is allocated either to beef or crop production. Reducing the number of stock on the hill and hence increasing the livestock in the lowland part of the farm, as represented by bringing animals to the lower arable ground more suitable for crop production and allocating the hill grassland only to categories of lower production requirements (dry cows and 2 year-old replacement heifers) seemed to provide a non-optimal solution in terms of both food production efficiency and GHG mitigation.

Nevertheless, it is important to remark at this point that the results obtained in this study are subjected to the assumptions made on the inputs and decision making as a response to alternative management. For instance, values of grass and crop yield, and pasture quality may vary in different locations and management of the system. In terms of decision making, it was assumed that land designated for either crop or grass production would be flexible and the number of animals on farm will be optimised after using different mitigation options. However, under the same situation farmers could have decided either to maintain the size of the herd or maintain the land for producing saleable crops. In these cases, resulting CO_2eq emissions per unit of total DP produced will differ. This highlights the importance of considering diverse possible decisions making under the same circumstances in future studies of the impacts of GHG mitigation options, to provide solid information to policy makers interested on unbiased responses to reduce carbon footprints form beef systems.

Other assumptions were made in order to estimate the CH_4 emitted by all the categories of animals of the system. For instance, CH_4 from calves at foot was estimated to be 6.5% of their GEI, whereas for the other categories CH_4 was estimated at a variable ratio depending upon the NewEqGEI. This different assumption lead to a step change in the relationship between the energy lost as CH_4 and the GEI when plotting all the animals in study (Figure 26). These results are in accordance to the different slope of this relationship predicted by the NewEqGEI compared to the constant ratio of 6.5% of IPCC (2006). Given the lack of information on the CH_4 emission rates from calves at foot, applying the IPCC equation to this category of animals was the only way to represent their contribution to the total carbon emissions at the system scale.

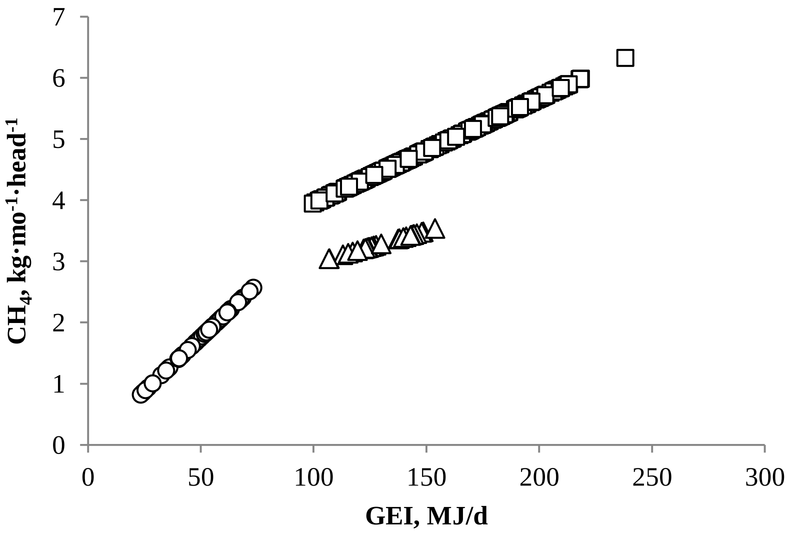


Figure 26. Relationship between methane (CH_4) emissions from all the simulated animals, predicted with the IPCC (2006) equation for calves at foot (circles), and with the NewEqGEI developed in Chapter 2 for animal fed either low-concentrate (squares) or high-concentrate diets (triangles).

Cattle are responsible for producing between 58 and 65% of the total CO_2eq.kg protein^{-1}.year^{-1} of the systems represented here (considering enteric and manure CH_4 and manure N_2O; Figure 20). Therefore, the question arises of what would have happened if no cattle had been reared on-farm and all suitable land would be allocated to cropping. Using the 69 ha in the lowland for barley production would have produced 56 tonnes of DP/year for human consumption with a carbon footprint of 215 t CO_2eq/year or only 4 kg CO_2eq/kg of protein produced. Considering the wide range on carbon emissions observed in this modelling exercise, even for the system observed to be the most efficient (HillAxL14), emissions ranged from 453 to 1024 t CO_2eq/year (12.2 to 30.5 kg CO_2eq.kg protein^{-1}.year^{-1}) when considering different sources of uncertainties. Thus, producing only crops would generate on average 20% of the carbon emissions per unit of human-digestible protein of the most efficient beef production system.

Nevertheless, this comparison could be debateable since no carbon sequestration was considered in this study. Considering a mean C sequestration potential of the hill grassland of -104 g $C.m^{-2}.year^{-1}$ (Soussana et al., 2007), results in -279.4 t C/year of carbon sequestration. Thus total emissions from beef systems would still be from 6 to 21 kg CO_2 eq.kg $protein^{-1}.year^{-1}$ higher than emissions from crop production. For future iterations of this model, including a module representing fluxes of C stocks as a result of different land use will be beneficial, particularly when comparing systems with different stock:crop balance. Values of carbon sinks are extremely variable depending on the characteristic of the farm (i.e. soil type, location, and climate) and its land use management, and also different from hill, lowland or arable land. Thus, these conclusions must be drawn with care. Moreover, consequences of reducing the number of grazing cattle are difficult to quantify. Under-grazing the hill vegetation, commonly characterised as moorlands or heathlands, has a negative effect on biodiversity conservation by allowing plants with more vigorous growth to over-top the more vulnerable species often more palatable and of good nutritive value for ruminants (Rosa García et al., 2013). In the lower ground, rotations between cropping and grazing help to avoid soil compaction, erosion and degradation (West and Post, 2002). Furthermore, subtracting livestock production affects livelihoods by reducing labour and job opportunities. If people want cattle to be produced, focusing grazing in the hill (i.e. reducing stock:crop balance of the farm allowing more crop production) is relatively the most important management alternative to both reduce GHG emissions and increase human-edible returns. Moreover, GHG predictions from systems adopting this management were more robust compared with the rest of the systems, hence combining high probability of low CO_2eq emission levels.

Therefore, one of the major conclusions of this work is that in relative terms, the extent of the use of the hill was the most important management option to reduce carbon emissions, followed by shortening the length of the finishing period and lastly the use of more efficient cattle genotype.

Previous studies have demonstrated that shortening the time of finishing reduces overall GHG emissions (Pelletier et al., 2010). The results obtained in the present study are in line with these findings. Further, this study suggests that some management alternatives were shown to work better in association with others. For instance, intensifying parts of the beef production system (such as shortening finishing period only) did not result in a reduction of GHG emissions if it was not accompanied by increments in efficiency of the whole system. Using a more efficient cattle genotype (AxL) helped to increase the returns of human-edible foods of the farm. Together with an efficient use of the land (grazing land unsuitable for cropping and cropping the arable land) the combination of these practices had the biggest impact on reducing emissions and increasing food production for human consumption.

The results of the present study have shown that alternative management options have diverse relative effects of GHG mitigation depending on the characteristics of the systems and the previous management adopted by a particular farm. In relative terms, using the hill grassland, with more cattle in the hill allowing a less grazing and more crop areas (low stock:crop balance), resulted in a system with lower CO_2eq emissions. Further technology applications to these hill systems had a relatively low impact when compared with lowland focussed systems. Systems focused on the lowland area, with longer finishing periods, where there are more animals on the improved lowland pasture and more animals fed indoors, was found to have more opportunity of reducing emissions by applying available technology (such as the use of additives, which can be fed most realistically to indoors animals only). A second major finding of this study was that the use of a hypothesised improved genotype for more efficiency had a wider impact on GHG mitigation due to its application to all the systems and all of the time.

These results contradict those mentioned by Moran et al. (2011) reporting higher abatement potential of the use of dietary additives (ionophores) than improved cattle genotype. However, these authors assumed lower genetic improvement and larger mitigation potential of the use of additives than those assumed in present study. Moran et al. (2011) also assumed that the GHG mitigation potential at the system level of the use of additives was the same as its impact at the individual animal level (e.g 25% reduction of CH_4 emissions by using ionophores). Moreover, in the mentioned study there was no distinction of the animal category on which these measures would be applied. In contrast, a more detailed representation of animal types and nutritional management was done in this chapter. This allowed specifying with more detail when and where these management alternatives have the opportunity to be applied, providing the main reason for the difference in the results observed between studies.

Although more detailed information was included in this chapter, results obtained in this study could be debateable from different points of views. Firstly, this study aimed to illustrate hypothetical examples of farming systems that may not represent the reality of a combination of management alternatives. However, examples represented here were useful to illustrate the interactions between variables that depend on a single decision making.

Looking in more detail, another point to discuss is that the model used for simulation is a deterministic and static model. This type of model does not allow for the study of mitigation effects in the long term scale. However, I believe this lack of inter-annual association was largely overcome in this study by including dynamic interactions between different components affected by a single mitigation management alternative. The model has also its limitations to represent changes of the input factors contributing with some uncertainty of the results. Although uncertainty was considered in DM digestibility values, the model does not account for changes on degradability of the protein, so an increment of the CP content of the feed results in a concomitant increment of N loss in manure. While the use of grass/clover swards have been mentioned to reduce GHG emissions of the farm due to the lower levels of fertiliser required, there is some controversy over its effect on enteric CH_4 emissions (Chaves et al., 2006; Archimède et al., 2011). In the model used for simulation in the present study, enteric CH_4 outputs and N excretion are each sensitive to changes in DMD and CP content of the feed, respectively. Thus, the CO_2eq emissions observed here reflected the balance between higher emissions due to higher N excretion and lower emissions due to less use of inorganic fertiliser. Misbalance of water soluble carbohydrates (WSC) and CP in ruminant's diets could lead to an increased excretion of N that cannot be efficiently utilised by microorganisms in the rumen. Results of the present study could be arguable, as the use of high WSC varieties of ryegrass in mixture with white clover could proportionate a balanced supply of energy and protein to the rumen (Evans et al., 1996) and avoid further losses of N in manure.

Also, the model used in this study did not represent changes in pasture yields and quality as a result of different levels of fertilizer application. Although some studies have demonstrated changes on the protein content of fertilised pastures of temperate (Reeves et al., 1996) and tropical (Davison et al., 1985) species, there is still some controversy in the literature as other authors did not find variation on digestibility, microbial N production and VFA concentrations from pastures under different levels of N fertiliser (Mackle et al., 1996). For future applications of this model, including a module to estimate the productivity of the land will be useful to represent management options of pastures or crop yields in response to the application of GHG mitigation alternatives.

The use of a constant CH_4 reduction potential of dietary additives could be debated as well, as for example, studies in the literature have mentioned that CH_4 mitigation potential of ionophores decrease over time as a result of rumen micro-flora adaptation (Beauchemin et al., 2008). However, this modelling exercise helps to illustrate the fact that only indoor animals receive this treatment and therefore the mitigation potential is much lower when accounted at the system level (up to 4.5% reduction), compared to the 20% assumed mitigation at the individual animal level.

Secondly, in more general terms some sources of emissions and sinks were not considered in this simulation, such as emissions of CO_2eq associated with land use change, use of electricity, pesticides, changes of soil carbon stock (Weiss and Leip, 2012), resources pollution and eutrophication risk of water sources (Pelletier et al., 2010). Including sensitivity to these changes could provide a more accurate estimate of CO_2eq emissions, particularly as different use of the land was compared as a management alternative. Although future iterations of this model could be enhanced by including such changes, there is lack of evidence of, for instance changes in soil carbon stock (Buckingham et al., 2013), or large uncertainty of the observed results due to high variation of GHG emission factors, contributing with more than 50% of the variation, hence more information is needed to provide accurate estimates of the effect of the use of the land on carbon budgets. Although more accurate predictions of CH_4 outputs were included, there is still large uncertainty due to N_2O emission factors.

Still, this study has demonstrated that although with large uncertainty, extensively but efficiently managed beef production systems have less opportunity to apply some of the available technology to further reduce their low carbon footprints. If intensification is understood to be taking the cattle off the hill and intensifying beef production in the lower ground, then systems adopting this intensification did not reduce their carbon footprints. If intensification is restricted to the beef enterprise only then systems with more intensive finishing period reduced emissions per kg of carcass in both hill and lowland based systems. However, the intensification of the beef sector competes with crop production on the better quality land. As cropping is a less “carbon intensive” activity intensifying beef production in the lower ground did not result in lower emissions. Therefore, if intensity is combined with “rational” use of the land, then grazing the land unsuitable for cropping and reducing the use of arable land for beef production and doing it intensively, reduced total emissions and emissions per total human-edible protein produced from both the beef enterprise and the whole-farm. It is therefore important to consider which metrics are used to compare farming systems and what is meant when referring to intensification of the agricultural sector in order to send the correct message to stakeholders and policy makers.

Although CO_2eq emissions per unit of product give an indication of the balance between productivity and carbon footprint, complementary work is needed to evaluate the profitability of these examples and analyse potential trade-offs between GHG mitigation and financial results of the implementation of the GHG mitigation alternatives described in this study. Further consideration of these results would have to be made in terms of the opportunity for alternative management or technology adoption, which certainly depends on the characteristics of the farm (Waghorn and

Clark, 2006) and the typology of farmer, which differ hugely in their reasons for the adoption of a given management application. Practices linked to increases on profitability of production systems are more likely to be adopted in practice (Waghorn and Clark, 2006; Sejian et al., 2011). External factors such as subsidies, policies and prices of products and commodities will have an impact on farmer's decision making (e.g. number of animals, seasonality, time of finishing, use of external inputs). Overall, there is more room for improvement of these modelling exercises to represent the actual variation on adoption of available technology to reduce environmental impact of beef farming systems and to study their impacts on social aspects of different livelihoods.

5.5 Conclusion

Farming systems analysed in this study illustrate a range of possible situations not only in Scotland and the UK, but also globally, where there are choices in farming the land intensively for either cropping or stocking, or using poorer land unsuitable for crops but being used by livestock with different degree of intensity. This study has demonstrated that beef production systems with a high proportion of their land unsuitable for cropping but with an efficient use of the good quality land in a crop:grazing rotation, had low GHG emissions and showed small opportunities to further reduce their carbon footprint per unit of product. Therefore, it supports views that farmers should be encouraged to maintain such systems as a national or global strategy to reduce overall GHG emission from food production.

The success of suggested management technologies applied to these types of systems on reducing GHG emissions rather depends on the characteristics of the farms and management previously adopted. Carbon emissions from more efficient systems in terms of GHG emissions, human-edible returns and biodiversity conservation are more certain, compared with less efficient systems.

Focusing the grazing herd in the hill grassland was the alternative which had a bigger impact on reducing emissions per unit of product, followed by finishing cattle in shorter periods and using a more efficient cattle genotype. Alternative technology application was more effective on reducing GHG from the whole-system by utilizing an improved genotype, then level of fertilizer, type of sward and finally use of dietary additives. This relative order of importance of mitigation options depends on the metrics used, as interactions were observed when expressing total GHG emissions per farm, per 100 cows herd, per kg of beef or per kg of total product.

This study demonstrates the importance of the whole-farm system analysis. For some mitigation options their impact at the whole farm level was reduced compared with their individual effect due to the limitation of their application to only parts of the system (e.g. use of additives favours systems with more indoor feeding), whilst other mitigation (more efficient animals) were more universally mitigating and their impacts were more consistent.

Several opportunities for mitigation were represented in this study. These have focused on the impact upon emissions only. However, there are still considerable interactions between GHG emissions and other farm issues related to costs for implementing a given management, and its associated labour, and impacts on biodiversity and pollution that should be considered in further studies.

Mitigation strategies of the carbon burden of agriculture need to be focused at the system level and avoid conclusions from reductionist approaches when designing actions for reducing environmental impact of agricultural systems. This modelling exercise contributes valuable information for future research, highlighting the value of systems modelling to represent the complexity of the study of GHGs and food production when involving the diversity of farms and opportunities to apply available mitigation options at a national or global scale.

Chapter 6: General discussion and conclusions

6.2 Introduction

The objectives of this thesis were to identify gaps in the knowledge regarding the main factors affecting greenhouse gas (GHG) emissions from beef farming systems and to study the relative impact of management strategies and mitigation options at the whole-farm system level. Many specific issues have been discussed within each of the results chapters. The aim of this chapter is to discuss the overall findings of this work together with the limitations and challenges involved during the study and to suggest further studies of related topics.

Uncertainties of carbon footprinting are related to the large number of factors affecting the nutrient cycles in different inter-related parts of the system, the difficulty of their representation in a mathematical model or limitation of their actual quantification with available techniques, such as in extensive farming conditions.

6.3 Reducing uncertainty of methane predictions

6.3.1 Accurate methane models

As mentioned in Chapter 1, different approaches have been adopted for estimating GHG emissions in modelling studies. Broadly, either detailed mechanistic models are used to represent a chain of predictions that consider many factors each affecting the trend of the results, or alternatively more general empirical models are used for predicting GHG mitigation potential at the production systems level or national scale. Both approaches have their advantages and limitations when considered for a whole-farm level study. Detailed mechanistic models may not be accurately calibrated and validated for the particular conditions that the study is focused on, or there is lack of essential input values. As a result, extrapolations may be made without knowledge of their bias. On the other hand, more general models (such as the one suggested by IPCC, 2006), which can be widely applied to any situation, have the disadvantage of carrying large uncertainties due to generalized assumptions (Lovett et al., 2008; Foley et al., 2011).

In all cases, feed intake and diet nutritional value are the main predictors of CH_4 outputs from ruminants. However, it was demonstrated in Chapter 2 that 10% more variation in CH_4 predictions can be explained by including the effect of physiological stage in combination with level of concentrates in the diet to a CH_4 prediction model (Table 7). These equations were developed to fill the gaps in the knowledge regarding CH_4 emissions yields from cattle of different characteristics and under diverse management normally found in a cattle breeding-finishing system. To my knowledge, this is the first time that the effect of physiological stage on CH_4 predictions was evaluated and a set of equations (NewEq) was established for their application in system analyses. This study has proven that there is an additional advantage for predicting CH_4 outputs over the current standard IPCC method (IPCC, 2006).

As described in Chapter 1, several mathematical models have been published for application to a particular type of animals under certain type of diets. Generating local emission factors is valuable to obtain more accurate estimations at a given situation. However, when scaling the study up to the national or global scale, equations considering a wider range of situations are required to avoid extrapolations. Yet, these equations and models also need to function well with the type of data available in practice. To study factors that affect CH_4 emissions at a wider scale, a meta-analysis approach was adopted in Chapter 2. The advantage of gathering information from different studies is to take into account deviations from one study to another (Sauvant et al., 2008). Although CH_4 estimates produced with some of the equations generated in this thesis (lactating cows fed low-concentrates and non-lactating fed either high- or low-concentrates) were in agreement with observed CH_4 measurements, further studies are needed to investigate the potential advantage of the use of the equations developed for lactating high-concentrates fed animals against observed measurements because of a lack of data for this animal and diet type combination for its validation. As I have demonstrated, however, using a more diverse set of equations does reduce uncertainties of CH_4 predictions at the animal and whole-farm systems scales compared with the current simple IPCC approach.

One of the limitations of using this empirical approach for modelling GHG budgets is the lack of sensitivity to other factors not included in the model (France and Kebreab, 2008). Given the considerable effort going into mitigation it would be useful to include mitigation treatments in CH_4 prediction models. For instance changes in CH_4 emissions as a result of the use of dietary additives, plants with secondary compounds, among other examples, that have been proven to reduce CH_4 yields, as mentioned in Chapter 1. Although factors such as the presence of treatments to mitigate CH_4 production or restricted level of intake were considered for the model fitting process in Chapter 2, the inclusion of these variables did not explain further variation in observed CH_4. Perhaps this result reflects simple discrepancies between studies or the wide range of results regarding the level of mitigation potential of these dietary supplements across studies. It is therefore important to consider the CH_4 mitigation potential of dietary additives under different management conditions in future meta-analyses studies for their further representation in modelling exercises.

The suitability of available information regarding the quality of the diet selected by grazing animals was also identified. It was observed in Chapter 2 that by matching actual performance data of grazing cows with digestibility values from the literature, the predicted intake values were higher than expected for the type of animals and their physiological stage. This is clearly highlighting the need to consider grassland selectivity when predicting carbon emissions from extensive systems where animals are grazing for most or all the year. Available models to predict CH_4 emissions have not been well validated for grazing animals and improvements of the methodology to estimate the digestibility of the selected diet should be pursued.

Being able to represent the factors that contribute to variation in GHG emissions for a given situation and to scale up more accurate results to the system level is important to obtain accurate carbon budgets at the national and global levels. Representing the diversity of situations where a given mitigation option can be applied is also important to design adequate policies that encourage the desired response at the national level.

6.3.2 Methane output and grazing behaviour

Behaviour associated with grazing activity is one of the major factors contributing uncertainty to CH_4 predictions. The difficulty of performing actual measurements of CH_4 and intake from extensively managed herds without disturbing animals' natural behaviour is still of major concern. Pasture selectivity is often avoided in experimental studies which use small plots on deliberately homogenous pastures, as unknown plant selectivity contributes to the pool of inter-animal unexplained variation, and difficulties in characterising the grazed intake. As a result, there are virtually no emissions data for free-ranging cattle on diverse pastures. These issues were illustrated in Chapter 3. Although models have been developed to represent grazing behaviour (e.g. Armstrong et al., 1997a; Armstrong et al., 1997b), the application of these types of mathematical grazing models to GHG emission studies has not been undertaken before. Furthermore, previous studies have mentioned differences in natural foraging behaviour between breeds and their management condition (Funston et al., 1991; Hessle et al., 2008). But how these impact on GHG emissions has not been reported previously. Thus, as cattle breed is an important factor to characterise animal performance and predicted feed intake in national inventory reporting systems and variation in the relative use of extensive pasture were important issues identified, I thought to be pertinent to study the potential effect of observed grazing behaviour and activity patterns on CH_4 prediction in a modelling study. Technology is now available to remotely study the natural behaviour of animals and these were implemented in a long-term study of diverse cattle breeds grazing semi-natural hill vegetation in South-East Scotland (Umstätter et al., 2009). The database generated from this study was used for a modelling exercise as described in Chapter 3. Results clearly demonstrate that variations in grazing behaviour and grazing choice have a potentially large impact upon CH_4 emissions that are not normally mentioned within carbon budget calculations both at local and national scales. The high sensitivity of CH_4 predictions to changes in quality of the diet highlights the importance of considering cattle foraging behaviour and selectivity on heterogeneous grasslands for carbon budgeting. At the farm-system level, this study demonstrates that differences on CH_4 outputs in response to diverse grazing behaviour can be as important as varying reproductive efficiency.

As the aim of this study was to clarify the role of different factors in cattle grazing, I had to clarify and characterise some of the uncertainties involved in this modelling study. Hence sensitivity analyses were performed to account for the effects of potential bias on the simulated results. Some of these issues are worth discussion. As described in Chapter 3, results were highly sensitive to changes in digestibility of the diet, thus this study suggests considering grazing selectivity on GHG studies. Still, this result also highlights the challenge of performing measurements on extensive free-range herds grazing heterogeneous grasslands where animals have the chance to express their natural behaviour involving diet selection. Furthermore, methods to measure pasture intake, quality and CH_4 emissions are either not available or not appropriate for their application in those environments. There is a clear potential to develop remote sensing and telemetry techniques that allow more accurate measures of some of these variables without disturbing the natural behaviour of grazing cattle if more precise estimates of the potential environmental impact of grazing cattle need to be obtained. The scale of this issue is illustrated by the large area of land used by cattle in extensive systems (70% of the world's agricultural area; FAO, 2010) and by the global debates about modifying the intensity of management (Godfray et al., 2010). Therefore, these debates need to be informed by science.

Values reported in the literature for the quality of the grazed species were used for simulation. Although it would have been ideal to measure the quality of the selected vegetation, measuring grassland quality is a difficult task given the characteristics of the range where the cattle were grazing. The dataset of cattle behaviour used in this study was originated from 45 cows with calves at foot in a grazing area of up to 287 ha. The location of the animals was unknown until information from the GPS collars and activity sensors was collected, processed and analysed. Simply performing direct measurements of grassland quality and using these as predictors of animal intake without knowledge of the selection of different habitat and species patches by the animals would have given biased estimation of the selected diets, as cows spend different proportion of their grazing time on different plant communities. Thus, information of the quality of the grasses present in the vegetation chosen by cattle was used instead of an average value. Undertaking further measurements of grassland quality by following the animals, or estimating feed intake (using faecal markers) or measuring CH_4 (using sulphur hexafluoride technique) that require daily gathering of the herd, would have affected the expression of the natural behaviour, animal physical activity, energy requirements and further factors for which natural behaviour was studied of cattle grazing in these extensive conditions. A simulation approach has been adopted for predicting the contribution of wild animals to CH_4 emissions (Hristov, 2012) or to compare the level of emissions today to more than 30 year ago (Capper et al., 2009; 2011) providing valuable information of trends when no data is available. However, to my knowledge this is the first time that a large and unique dataset (with several million grazing locations) with behavioural data and diet selection is included in a CH_4 modelling study. For that reason, I believe the modelling approach undertaken in the current study contributes valuable information of trends that can be expected from these farming conditions and suggests the consideration of grazing behavioural features of diverse cattle genotypes for future research on carbon footprints. This further illustrates the value of more studies of CH_4 (and linked environmental impacts) upon the world's diverse rangeland resources.

6.3.3 Novel technique for methane remote sensing

As mentioned above, part of the limitations for collecting reliable information from grazing cattle is due to some disadvantages of available techniques to perform CH_4 emission measurements. Yet, measuring CH_4 is crucial for understanding cattle behaviour (and *vice versa*) and providing the basic data for modelling studies. Thus, the potential use of a novel technique was evaluated with the objective to assess its potential application for remote sensing of CH_4 emissions. The Laser Methane Detector (LMD), developed as monitoring equipment, was firstly suggested for its use in animal science in a study with dairy cows (Chagunda et al., 2009b). As part of this thesis, this device was fully validated against respiration chambers, currently the best and most acceptable method for CH_4 measurement, on sheep and cattle after its use for extremely short periods of time (2 and 4 min, respectively), in comparison with current methods. The new method for the analysis of LMD outputs obtained as a result, demonstrated that the LMD was able to differentiate CH_4 emissions from different diets and detect reduction on CH_4 concentrations after offering fresh food, in accordance to what was expected from previous more invasive studies (Blaxter and Joyce, 1963). On account of its high frequency of data output and sensitivity of measurements compared with other available methods, the LMD has the potential to discriminate CH_4 emissions from normal respiration and from eructation, in agreement with previously reported ranges (Murray et al. 1976). This characteristic adds another advantage to the LMD for its application on nutritional studies, together with it easily portable dimensions and weight, ease of use, low cost and maintenance, and its potential direct and practical application for monitoring on-farm CH_4 emissions at different locations without involving the use of additional equipment and laboratory analysis. Furthermore, measurements with this technique can be obtained while animals are handled for other purposes, such as weighing, pregnancy detection, animal health treatments depending on the type of farm and management conditions, meaning that either no extra time or no additional operator is required. However, much more work is needed with the LMD to be able to quantify CH_4 emissions from animals under diverse management situations and its potential application on outdoors conditions. So far, the LMD cannot predict amount of CH_4 without other direct method that measures amount of CH_4 for its validation, nor is it easy to see how it might. Further, rankings of animals measurements, which would be valuable from a practical point of view, were poorly related with the standard chamber measurements without further data processing. More studies are needed to investigate other methods for processing spectral type of data, improving data handling and obtaining rankings of measurements in a more direct way. If this ability to rank animals can be validated, this device has potential application for genetic improvement programs, *in situ* mitigation testing of for instance dietary treatments, or monitoring background levels of CH_4 at the cattle shed level.

Although laser methodology has been demonstrated to provide remote CH_4 sensing to measure concentrations of CH_4 outputs, laser based multiple-gas measurement technology is available to quantify CH_4 together with CO_2. The ratio of these 2 gases can be used to estimate CH_4 outputs based on predicted CO_2 emissions according to animal performance (Madsen et al., 2010). Thus, adapting this technology for application in animal science could potentially contribute to solve some of the challenges of quantifying CH_4 remotely from laser methods and would be an interesting area for future studies.

6.4 Relative importance of greenhouse gas mitigation options

Globally, there is large heterogeneity on the types of farms and their characteristics. The reasons that motivate farmers to decide among available management options vary especially as there is a range of farming systems, from large enterprises more involved into the business of commodity sale of animal products (such as Brazil, Argentina, among others) to subsistence farming in poor rural areas (Sub-Saharan Africa, South-east Asia, FAO, 2012). Income growth and changes in food consumption are happening and demands for food are expected to grow (FAO, 2012). Thus, understanding how livestock systems can adapt to changes in decision making is critical for studying the opportunities for “sustainable intensification”.

In the fifth and last results chapter of this thesis, management strategies covering a range of intensities and GHG mitigation options suggested in the literature were analysed in a whole-farm simulation study with a holistic point of view using mechanistic empirical models. Improvements in the accuracy of predicted carbon footprint from beef production systems were incorporated into the model. This was achieved by utilizing the more appropriate and sensitive set of equations for predicting CH_4 from animals on different physiological stages in combination with diet types produced in Chapter 2, more accurate estimates of animals’ activity on hill grasslands used in Chapter 3, and more detailed information regarding herd and land use management. This new approach contrasts with the standard methodology used in IPCC (2006), generally utilized for predicting environmental impact of whole-farm systems in national inventories.

This model comprises the results described above to reduce the uncertainty of CH_4 predictions. It also interacts with the SAC C-calculator (RBU, 2011) to obtain predictions of GHG from the other part of the farm system (e.g. arable). The SAC C-calculator is based on Tier 1 IPCC approach (IPCC, 2006) for predicting whole-farm carbon emissions. The utilization of the full version to compare alternatives for GHG mitigation was decided against due to the advantage of the NewEq over the IPCC (2006) methodology as demonstrated in previous chapters. Carbon budgets estimated with the full version of the SAC C-calculator results in 16% higher emissions than those estimated for the baseline systems as mentioned in Chapter 5 (799 vs. 690 t $CO_2eq.yr^{-1}$, respectively). This difference not only reflects the use of the NewEq but also the use of a more sensitive time scale able to capture changes in physiological stage, diet quality and their interaction over the year which cannot be represented with the SAC C-calculator due to its structural limitations. SRUC has up-dated its SAC-C calculator with new data from its own crop trials, hence it could consider up-dating its beef part of the programme considering some of the results produced in this thesis.

This study performed at different levels of complexity reveals advantages of improving accuracy of predictions at the animal level when considering carbon footprints of beef production systems. Different levels of complexity of models (i.e. detail of inputs needed) will be determined by the information available on each particular situation under study and the objectives of the application of the model. This simulation study shows that important differences are expected while predicting carbon footprints based upon a methodology that is able to reflect important changes happening in a system that are directly related with GHG emissions in comparison with more generalised models. Thus, understanding how GHG are produced, how and how much they respond to determinant factors were essential steps undertaken in this thesis to further improve GHG predictions and to test alternative management for their mitigation. An alternative approach to study GHG mitigation strategies at the system level is the use of the Life Cycle Assessment (LCA) methodology (Cederberg et al., 2013). Although one of the aims of this thesis was to study alternatives to reduce GHG from beef production systems, much of the uncertainties of CH_4 predictions are within the farm gate. Thus, this study was focussed on this part of the food production chain and conclusions from this work will help to inform global LCA of this sector.

In this thesis, alternative management options of a beef breeding-finishing baseline system are compared, considering not only their impact on GHG emissions and productivity, but also the returns of human-edible food and their potential impact on biodiversity conservation programs as an illustration of wider impact of the system management. Although the obtained results are highly subjected to the assumptions made in this study (Chapter 5) they have demonstrated an important interaction of intensity of management with other mitigation options on the overall CO_2 equivalents (CO_2eq) emissions per unit of product of the system. The modelling results reveal that the impact of diverse mitigation options are relative to the characteristic of the systems they are applied within. Their impact at the system level differs with that claimed from animal based studies at the individual level and impacts are generally diluted when analysed at the system level.

Several GHG mitigation options have been proposed in studies at the animal or system level and described extensively in Chapter 1. However, the novelty of the work undertaken in Chapter 5 is the analysis of their relative importance to the whole system carbon footprint mitigation. Overall impacts of mitigation alternatives differ from their individual effect due to interactions with other factors in the system, in some cases having up-to 10-fold lower mitigation potential when studied at the system level than their impact on individual animals. Their importance was also relative to the type of system in which management are applied and its characteristics.

It is widely assumed that the application of given mitigation options can reduce net CO_2eq emissions of all systems under analysis (MacLeod et al., 2010; Moran et al., 2011). Yet this hypothesis was observed to be inconsistent, as the effect of different mitigation options varied in relation to the characteristics of the system under study. More efficient systems showed limited opportunity to further reduce their emissions by using for instance dietary additives or grass/legumes mixed swards, management that affect a smaller proportion of the simulated system. This modelling exercise helps to illustrate that information regarding the level of adoption of a given mitigation practice, opportunity for its application and/or proportion of farms or situations where it can potentially be used, need to be taken into consideration in system analysis studies of regional, national or global carbon footprints. Different countries such as Scotland, Argentina or those in Sub-Saharan Africa have not only different biological characteristics and typology of farms with diverse objectives (i.e. subsistence, internal market or commodity traits) but they also differ on their historical records of technology adopted by different typology of stakeholders, and these differences have to be considered when studying GHG mitigation at the global scale and when designing programmes for global scale carbon burden abatement.

Results from Chapter 5 showed that interactions and trade-offs will take place between climate change issues, issues of relative intensification and natural heritage issues depending on the management adopted. For instance, if only using the arable land for cropping, selling all the livestock on-farm and producing only vegetarian food for human consumption is an option; then this statement cannot be rejected. Although this management option would have the lowest carbon footprint, loss of biodiversity of traditional semi-natural pasture and abandoned land, and economic repercussions on the livelihood of the area would be disadvantages of this decision. Moreover, consequences of these changes may have to be studies in a long-time scale, as for instance carbon sequestration potential, soil erosion, or even long term impact of climate change on crop yields and grasslands. Consequently, the adequate utilization of semi-natural grasslands by grazing cattle together with an efficient use of the arable land available resulted in the more appropriate decision both in terms of lowering carbon footprints, increasing human-edible returns and maintaining biodiversity of this vulnerable areas, without negative effects on the livelihood of the region.

These simulation results suggest that an efficient use of the land (poor land for grazing, better land for rotational cropping and grazing) is the most efficient management to reduce GHG without compromising food production and biodiversity conservation. Farmers should be encouraged to move towards efficient production systems in a sustainable way, as suggested in the term “sustainable intensification”.

Nevertheless, there is a risk of this recommendation being misleading. Most of the time, intensive beef farming equates to allocating animals to better quality land and increasing the production and use of higher energetic fodder for an efficient and intensive nutritional management. The suggestion of intensifying farming systems should be therefore complemented with the idea of a “rational use of the land”.

This farm modelling exercise reflects at some point some of the issues experienced at the global scale, as represented with different characteristics and typologies of farms, diverse land quality and land use opportunity. These results are of relevance not only for countries such as Scotland and Argentina which have lots of rangelands grazing, but also for the entire globe as representing issues related with the use of the land in situations with reduced opportunities to produce food and sustain livelihoods. Scaling up the modelling approach described in this study to a global scale would be shown to be most efficient, as it considers a set of different issues related with interactions between climate change and food production.

Further studies considering financial information in this simulation exercise would provide a more comprehensive understanding of trade-offs from the scientific and economic points of views. Ruminants have the advantage of being able to utilise by-products from other industries, which produces multiple benefits, such as reducing industry wastage, intensifying beef farming, and reducing the competition between crop production for animal feeding vs. human-edible food. More research is also needed on alternatives for crop and soil management (e.g. rotations, tillage, nitrogen inhibitors) to further investigate interactions related to the characteristics of the system (i.e. location, type of land, climate) and conclude about best combination of practices for GHG mitigation. Moreover, there is a need to evaluate long-term trade-offs of mitigation alternatives applied to different constituent of the agricultural system while considering problems beyond GHG burden of food production, but also related issues such as energy demands (Johnson et al., 2007). Reducing the number of ruminants would be a rapid solution but not well adapted for those who rely on animal products for their own consumption or for sale to others (Reid et al., 2004). Mitigation options should be studied in a global context where the spatial, temporal and cultural variability are considered when designing alternatives for efficient and sustainable food production.

6.5 Conclusions

With still 870 million people chronically undernourished in 2010–12 and the global demand for food expected to increase by 60% by 2050 (FAO, 2012) it is critical to study ways to mitigate the environmental impact of livestock production which produce food from areas where no crops can be produced. This work comprises the study of outputs of greenhouse gases from the molecular level, as measured with a novel and sensitive devise, to the study of carbon footprints and consequences of mitigation at the whole-farm system scale. Understanding how CH_4 is produced from ruminants and identifying which factors affect its determination are crucial to reduce the uncertainty of its prediction. Thus, this thesis concludes that:

1) A series of more specific mathematical models to predict CH_4 from ruminants under different physiological stages and diet types reduced the uncertainty of whole-farm enteric CH_4 predictions by up-to 7% over a year and this approach should be taken into account for future system carbon footprint analyses.

2) The diverse grazing behaviour of cattle breeds grazing extensive rangeland has a potentially large impact on CH_4 emissions, suggesting that different grazing patterns of cattle on heterogeneous grasslands should be considered for future assessments for carbon footprint mitigation from beef farming in these environments.

3) The use of a novel technique to assess CH_4 production from ruminants showed very good correlations with independent measurements in respiration chambers. Moreover, the use of this highly sensitive technique demonstrates that there is more variability associated with the pattern of CH_4 emissions which cannot be explained by the feed nutritional value.

4) The assessment of contrasting systems under diverse management strategies including GHG mitigation alternatives on each type of system have shown that efficient and robust production systems with high proportion of their land classified as less favourable have limited opportunities to intensify their management and further reduce their carbon footprint without trying to avoid losses of biodiversity of valuable grasslands and impact on local livelihoods.

5) The efficacy of GHG mitigation measures is system dependent, thus generalisations of expected impacts should be avoided. Further, most mitigation impacts at the individual animal level are diluted when scaled up to the farm system level, hence holistic instead of reductionist approaches for the study of GHG mitigation strategies is recommended.

6) The scale and direction of success in reducing emissions also depends upon or interacts with the metric of measurement, with differences seen between outputs of GHG per farm, per herd or per kilogram of outputs. However, trade-offs between issues related with climate change and food security can be avoided if conclusions are based upon GHG emissions per kilogram of human-edible products.

Altogether, this work highlights the essential role of studies with a holistic approach to issues related to climate change that encompass the analysis of large ranges of situations and management alternatives which can be applied to a global scale. Overall, these results will help to obtain more reliable predictions of CH_4 outputs in farm-scale models, in national inventories, and more accurate mitigation studies and cost/benefit analyses from the system level, contributing with valuable information to full Live Cycle Assessments of the beef sector and provide detailed evidence for other scientists, economists, and policy makers. Future experimental work based on systems analysis will be critical to study the contribution and interactions of new arising technologies developed to improve the efficiency of sustainable agricultural systems.

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Appendix

Results obtained in Chapter 5 after simulation of alternative options were presented in graphs. In this appendix detailed information of the changes relative to the baseline system described is presented.

Table 35. Changes (%) in carbon dioxide equivalent emissions (CO_2eq) relative to the baseline strategy (Pure grass, Current Genotype, 250 kg N/ha and No additives)

Lowland	Pure Grass							Grass/clover							
Genotype	Current			Efficient				Current				Efficient			
Fertiliser	250	125		250		125		125		0		125		0	
Additives	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Total CO_2eq, tonnes/year															
HillLUI24	-4	-16	-19	-6	-10	-20	-23	-6	-10	-16	-20	-6	-10	-21	-25
HillAxL24	-4	-9	-12	1	-3	-14	-17	-6	-9	-14	-18	1	-4	-14	-19
HillAxL14	-3	-5	-8	4	1	-1	-4	-3	-6	-8	-11	1	-2	-4	-8
HillLUI14	-3	-5	-8	5	2	-1	-4	-3	-6	-8	-11	1	-2	-4	-8
LowlandLUI24	-4	-20	-23	-3	-6	-21	-24	1	-3	-21	-25	-2	-7	-22	-26
LowlandAxL24	-4	-20	-23	-3	-7	-21	-24	1	-3	-20	-24	-2	-7	-22	-26
LowlandLUI14	-3	-19	-22	-3	-7	-21	-24	4	1	-17	-20	0	-4	-19	-22
LowlandAxL14	-3	-19	-22	-3	-7	-21	-24	4	1	-17	-20	0	-4	-20	-23
Total CO_2eq, tonnes·100 cows herd^{-1}·year^{-1}															
HillLUI24	-4	-6	-10	-11	-14	-16	-20	-6	-10	-15	-19	-19	-23	-24	-28
HillAxL24	-4	-9	-12	-14	-17	-19	-22	-6	-9	-14	-18	-21	-25	-26	-29
HillAxL14	-3	-5	-8	-18	-21	-22	-25	-3	-6	-8	-11	-21	-23	-25	-28
HillLUI14	-3	-5	-8	-18	-20	-22	-25	-3	-6	-8	-11	-20	-23	-25	-28
LowlandLUI24	-4	-9	-13	-11	-14	-19	-22	-12	-16	-21	-25	-21	-25	-29	-32
LowlandAxL24	-4	-9	-13	-12	-15	-20	-23	-12	-15	-20	-24	-22	-25	-29	-32
LowlandLUI14	-3	-8	-11	-13	-16	-20	-23	-10	-13	-18	-21	-22	-25	-28	-31
LowlandAxL14	-3	-8	-11	-14	-17	-21	-24	-10	-13	-18	-21	-23	-25	-29	-32
Total CO_2eq, tonnes·kg meat+grain Protein^{-1}·year^{-1}															
HillLUI24	-2	-3	-5	-11	-12	-13	-14	-14	-15	-7	-9	-14	-15	-16	-17
HillAxL24	-1	7	6	0	-1	-2	-3	-8	-9	-4	-5	-3	-4	-5	-6
HillAxL14	0	0	0	1	1	2	1	-2	-2	-1	-2	-1	-1	0	-1
HillLUI14	-1	1	0	2	1	3	2	-2	-2	-1	-2	-1	-1	0	0
LowlandLUI24	-2	-4	-6	-11	-12	-14	-16	-6	-7	-10	-12	-15	-17	-18	-20
LowlandAxL24	-2	-4	-6	-11	-12	-14	-16	-5	-7	-9	-11	-15	-16	-18	-19
LowlandLUI14	-2	-6	-8	-19	-21	-23	-25	-6	-8	-11	-13	-24	-25	-27	-28
LowlandAxL14	-2	-5	-7	-18	-20	-22	-23	-6	-8	-11	-13	-22	-24	-26	-27

Table 36a. Changes (%) in carbon dioxide equivalent emissions (CO_2eq) relative to the baseline strategy (Pure grass, Current Genotype, 250 kg N/ha and No additives) from individual gases and sources

Lowland	Pure Grass							Grass/clover							
Genotype	Current			Efficient				Current				Efficient			
Fertiliser	250	125		250		125		125		0		125		0	
Additives	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Enteric CH_4, tonnes CO_2eq/year															
HillLUI24	-8	-10	-17	-5	-13	-14	-21	0	-8	-1	-9	5	-4	-6	-14
HillAxL24	-8	0	-8	5	-4	-4	-12	0	-8	0	-8	14	5	3	-5
HillAxL14	-6	0	-6	11	4	11	4	0	-6	0	-6	11	3	11	3
HillLUI14	-6	0	-6	11	4	11	4	0	-6	0	-6	11	4	11	4
LowlandLUI24	-9	-12	-19	0	-9	-11	-19	12	2	-3	-11	11	1	-2	-12
LowlandAxL24	-8	-11	-19	0	-9	-11	-19	12	2	-3	-11	11	0	-3	-12
LowlandLUI14	-7	-11	-18	-1	-8	-12	-18	12	4	-2	-9	10	2	-3	-10
LowlandAxL14	-7	-12	-18	-1	-8	-12	-18	12	4	-2	-9	10	2	-3	-10
Manure CH_4, tonnes CO_2eq/year (directly deposited + managed manure)															
HillLUI24	0	-10	-10	-11	-11	-19	-19	-1	-1	-3	-3	-3	-3	-13	-13
HillAxL24	0	0	0	-2	-2	-11	-11	-1	-1	-1	-1	5	5	-5	-5
HillAxL14	0	0	0	3	3	3	3	-1	-1	-1	-1	2	2	2	2
HillLUI14	0	0	0	4	4	4	4	-1	-1	-1	-1	3	3	3	3
LowlandLUI24	0	-11	-11	-7	-7	-17	-17	10	10	-5	-5	1	1	-12	-12
LowlandAxL24	0	-11	-11	-8	-8	-17	-17	10	10	-5	-5	0	0	-12	-12
LowlandLUI14	0	-11	-11	-9	-9	-18	-18	9	9	-5	-5	-1	-1	-13	-13
LowlandAxL14	0	-12	-12	-8	-8	-18	-18	10	10	-5	-5	-1	-1	-13	-13
Manure N_2O, Total tonnes CO_2eq/year (directly deposited + managed manure)															
HillLUI24	0	-10	-10	-20	-20	-27	-27	8	8	7	7	-3	-3	-13	-13
HillAxL24	0	0	0	-13	-13	-21	-21	7	7	7	7	3	3	-7	-7
HillAxL14	0	0	0	-5	-5	-5	-5	5	5	5	5	1	1	1	1
HillLUI14	0	0	0	-4	-4	-4	-4	6	6	6	6	3	3	3	3
LowlandLUI24	0	-12	-12	-17	-17	-26	-26	50	50	30	30	26	26	11	11
LowlandAxL24	0	-12	-12	-18	-18	-27	-27	51	51	31	31	25	25	10	10
LowlandLUI14	0	-11	-11	-16	-16	-25	-25	53	53	33	33	31	31	15	15
LowlandAxL14	0	-12	-12	-16	-16	-25	-25	53	53	33	33	31	31	15	15
Organic and Inorganic Fertiliser N_2O (volat, leach, runoff), tonnes CO_2eq/year															
HillLUI24	0	-32	-32	-1	-1	-31	-31	-28	-28	-61	-61	-29	-29	-58	-58
HillAxL24	0	-30	-30	0	0	-29	-29	-25	-25	-55	-55	-26	-26	-55	-55
HillAxL14	0	-16	-16	1	1	-17	-17	-14	-14	-30	-30	-14	-14	-32	-32
HillLUI14	0	-17	-17	1	1	-18	-18	-14	-14	-31	-31	-15	-15	-34	-34
LowlandLUI24	0	-37	-37	-1	-1	-36	-36	-34	-34	-70	-70	-33	-33	-66	-66
LowlandAxL24	0	-37	-37	-1	-1	-35	-35	-34	-34	-69	-69	-33	-33	-66	-66
LowlandLUI14	0	-37	-37	-1	-1	-36	-36	-34	-34	-69	-69	-33	-33	-66	-66
LowlandAxL14	0	-37	-37	-1	-1	-36	-36	-35	-35	-70	-70	-33	-33	-66	-66

Table 36b. Changes (%) in carbon dioxide equivalent emissions (CO_2eq) relative to the baseline strategy (Pure grass, Current Genotype, 250 kg N/ha and No additives) from individual gases and sources

Lowland	Pure Grass							Grass/clover							
Genotype	Current			Efficient				Current				Efficient			
Fertiliser	250	125		250		125		125		0		125		0	
Additives	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Crop residues N_2O (volat, leach, runoff), tonnes CO_2eq/year															
HillLUI24	0	-7	-7	2	2	-4	-4	10	10	-1	-1	9	9	1	1
HillAxL24	0	-9	-9	-1	-1	-7	-7	8	8	-1	-1	6	6	-2	-2
HillAxL14	0	-4	-4	-2	-2	-6	-6	4	4	-1	-1	2	2	-2	-2
HillLUI14	0	-4	-4	-2	-2	-7	-7	4	4	0	0	2	2	-3	-3
LowlandLUI24	0	-7	-7	4	4	-3	-3	9	9	0	0	13	13	4	4
LowlandAxL24	0	-7	-7	4	4	-3	-3	9	9	0	0	13	13	4	4
LowlandLUI14	0	-6	-6	4	4	-3	-3	8	8	0	0	12	12	4	4
LowlandAxL14	0	-6	-6	4	4	-3	-3	8	8	0	0	12	12	4	4
Diesel CO_2 direct, tonnes/year															
HillLUI24	0	-4	-4	5	5	0	0	4	4	0	0	10	10	5	5
HillAxL24	0	-3	-3	6	6	1	1	3	3	0	0	10	10	6	6
HillAxL14	0	-2	-2	4	4	2	2	2	2	0	0	6	6	4	4
HillLUI14	0	-2	-2	4	4	1	1	2	2	0	0	6	6	4	4
LowlandLUI24	0	-5	-5	7	7	2	2	8	8	1	1	16	16	9	9
LowlandAxL24	0	-5	-5	8	8	2	2	8	8	1	1	16	16	9	9
LowlandLUI14	0	-6	-6	7	7	1	1	9	9	1	1	17	17	9	9
LowlandAxL14	0	-6	-6	8	8	1	1	9	9	1	1	17	17	9	9
Fertiliser CO_2 (application + embedded), tonnes/year															
HillLUI24	0	-33	-33	-1	-1	-32	-32	-29	-29	-62	-62	-30	-30	-59	-59
HillAxL24	0	-31	-31	0	0	-30	-30	-26	-26	-56	-56	-28	-28	-57	-57
HillAxL14	0	-17	-17	1	1	-18	-18	-14	-14	-31	-31	-15	-15	-33	-33
HillLUI14	0	-17	-17	1	1	-19	-19	-15	-15	-32	-32	-16	-16	-35	-35
LowlandLUI24	0	-37	-37	-1	-1	-36	-36	-35	-35	-71	-71	-34	-34	-68	-68
LowlandAxL24	0	-37	-37	-2	-2	-36	-36	-35	-35	-71	-71	-34	-34	-67	-67
LowlandLUI14	0	-37	-37	-1	-1	-36	-36	-35	-35	-70	-70	-34	-34	-67	-67
LowlandAxL14	0	-37	-37	-1	-1	-37	-37	-36	-36	-71	-71	-35	-35	-68	-68
Feed purchased CO_2 (embedded), tonnes/year															
HillLUI24	0	-10	-10	-7	-7	-16	-16	0	0	-1	-1	2	2	-8	-8
HillAxL24	0	0	0	1	1	-7	-7	0	0	0	0	11	11	0	0
HillAxL14	0	0	0	6	6	6	6	0	0	0	0	6	6	6	6
HillLUI14	0	0	0	7	7	7	7	0	0	0	0	7	7	7	7
LowlandLUI24	0	-11	-11	-4	-4	-15	-15	15	15	0	0	9	9	-4	-4
LowlandAxL24	0	-11	-11	-5	-5	-15	-15	14	14	0	0	8	8	-5	-5
LowlandLUI14	0	-11	-11	-6	-6	-16	-16	15	15	1	1	7	7	-5	-5
LowlandAxL14	0	-11	-11	-6	-6	-16	-16	15	15	1	1	8	8	-5	-5

Table 37. Changes (%) in products and livestock numbers relative to the baseline strategy (Pure grass, Current Genotype, 250 kg N/ha and No additives)

Lowland	Pure Grass							Grass/clover							
Genotype	Current			Efficient				Current				Efficient			
Fertiliser	250	125		250		125		125		0		125		0	
Additives	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Meat, tonnes/year															
HillLUI24	0	-10	-10	15	15	4	4	0	0	-1	-1	27	27	14	14
HillAxL24	0	0	0	26	26	15	15	0	0	0	0	38	38	25	25
HillAxL14	0	0	0	36	36	36	36	0	0	0	0	36	36	36	36
HillLUI14	0	0	0	36	36	36	36	0	0	0	0	36	36	36	36
LowlandLUI24	0	-12	-12	19	19	6	6	15	15	0	0	36	36	19	19
LowlandAxL24	0	-12	-12	19	19	6	6	15	15	0	0	35	35	19	19
LowlandLUI14	0	-12	-12	19	19	6	6	16	16	1	1	37	37	20	20
LowlandAxL14	0	-12	-12	20	20	7	7	16	16	1	1	37	37	21	21
Barley grain, tonnes/year															
HillLUI24	0	-10	-10	25	25	13	13	45	45	-1	-1	38	38	24	24
HillAxL24	0	-30	-30	-5	-5	-13	-13	27	27	-4	-4	6	6	-6	-6
HillAxL14	0	-8	-8	-7	-7	-16	-16	8	8	-1	-1	2	2	-7	-7
HillLUI14	0	-9	-9	-9	-9	-19	-19	9	9	-1	-1	1	1	-9	-9
LowlandLUI24	0	-11	-11	29	29	15	15	15	15	0	0	47	47	29	29
LowlandAxL24	0	-11	-11	30	30	16	16	15	15	0	0	48	48	30	30
LowlandLUI14	0	-11	-11	49	49	33	33	15	15	1	1	70	70	50	50
LowlandAxL14	0	-11	-11	46	46	31	31	15	15	0	0	67	67	47	47
Total Digestible Protein (meat + crop), tonnes/year															
HillLUI24	0	-10	-10	22	22	11	11	35	35	-1	-1	35	35	21	21
HillAxL24	0	-25	-25	1	1	-8	-8	23	23	-3	-3	11	11	0	0
HillAxL14	0	-8	-8	-3	-3	-11	-11	7	7	-1	-1	5	5	-4	-4
HillLUI14	0	-9	-9	-5	-5	-14	-14	8	8	-1	-1	5	5	-5	-5
LowlandLUI24	0	-11	-11	27	27	13	13	15	15	0	0	44	44	27	27
LowlandAxL24	0	-11	-11	27	27	14	14	15	15	0	0	45	45	27	27
LowlandLUI14	0	-11	-11	38	38	23	23	15	15	1	1	57	57	39	39
LowlandAxL14	0	-11	-11	37	37	22	22	15	15	1	1	56	56	37	37
Total number of cattle															
HillLUI24	0	-33	-33	29	29	-4	-4	1	1	-3	-3	67	67	26	26
HillAxL24	0	0	0	66	66	31	31	0	0	0	0	101	101	61	61
HillAxL14	0	0	0	72	72	72	72	0	0	0	0	72	72	72	72
HillLUI14	0	0	0	75	75	75	75	0	0	0	0	75	75	75	75
LowlandLUI24	0	-30	-30	33	33	1	1	39	39	0	0	73	73	33	33
LowlandAxL24	0	-30	-30	36	36	4	4	39	39	-1	-1	76	76	35	35
LowlandLUI14	0	-37	-37	38	38	-1	-1	50	50	2	2	90	90	41	41
LowlandAxL14	0	-36	-36	40	40	2	2	48	48	2	2	91	91	42	42
Total breeding cows															
HillLUI24	0	-10	-10	5	5	-4	-4	0	0	-1	-1	17	17	4	4
HillAxL24	0	0	0	17	17	6	6	0	0	0	0	27	27	15	15
HillAxL14	0	0	0	27	27	27	27	0	0	0	0	27	27	27	27
HillLUI14	0	0	0	27	27	27	27	0	0	0	0	27	27	27	27
LowlandLUI24	0	-12	-12	9	9	-3	-3	15	15	0	0	25	25	9	9
LowlandAxL24	0	-12	-12	10	10	-2	-2	15	15	0	0	25	25	10	10
LowlandLUI14	0	-12	-12	12	12	-1	-1	16	16	1	1	28	28	12	12
LowlandAxL14	0	-12	-12	13	13	0	0	16	16	1	1	29	29	13	13