Evaluating the performance of diverse dairy systems

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Declaration

I certify that the work described in this thesis is my own, except where otherwise stated, and has not been submitted for any other degree or award.

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10th February 2020

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Published material

This thesis contains five chapters, published, submitted or intended for publication in peer-reviewed journals. The contents of the papers were written and prepared by the candidate with comments and assistance provided by respective co-authors. The spring calving and pasture based Moorepark Dairy Systems Model (MDSM), described in detail in Chapter 2, was constructed in Microsoft Excel by Laurence Shalloo (Teagasc) (Shalloo et al., 2004). The MDSM was re-parameterised in collaboration with Willie Ryan (Teagasc) and in consultation with Laurence Shalloo and a team of stakeholders. Further updates to the MDSM model were made by the candidate to carry out analysis in Chapter 3. Luiza Toma (SRUC) assisted with the methods in Chapter 4 and ran the DEA model, and Alasdair Sykes (SRUC) linked the carbon footprinting model AgRECalc to Model Risk (Vose Software) to run footprint simulations.

March, M. D., Shalloo, L., Roberts, D. J., & Ryan, W., 2017. Financial evaluation of Holstein Friesian strains within composite and housed UK dairy systems. Published in Livestock Science, 200, 14–22. (Chapter 2). Available online: http://openaccess.sruc.ac.uk/handle/11262/11215

March, M. D., Toma, L., Stott, A. W., & Roberts, D. J., 2016. Modelling phosphorus efficiency within diverse dairy farming systems - Pollutant and non-renewable resource? Published in Ecological Indicators, 69, 667–676. (Chapter 4). Available online: https://www.sciencedirect.com/science/article/abs/pii/S1470160X16302576

Thesis abstract

Quantification of technical and environmental measurements from agricultural systems is of interest for both scientific and social reasons, so that types, sources, and amounts of undesirable outputs can be understood, managed and reduced. This cross-disciplinary research provides a holistically measured comparison of diverse genetic lines managed within novel and conventional UK dairy farming systems by employing a range of indicators and modelling techniques alongside a visual representation of the milk production regimes. This research focussed on evaluating Holstein Friesian cows of high and national average genetic merit across four diverse UK dairy production systems, by measuring environmental, health and financial outcomes. Using a Life Cycle Assessment approach and internationally agreed methods, performance indicators were used to assess the efficiency of dairy farming systems.

Obtaining greater yields at the expense of high costs was shown to be financially unsustainable, especially under fluctuating milk prices. Management decisions have a clear effect on profitability, as herd replacement and reproduction choices alter the lifetime production of a cow, and the age profile of a herd. Reducing replacement rate by 1% could increase profit by 0.3p per litre in housed management and 0.4p per litre in a grazed system. Long term breeding for milk, fat and protein yield led to an average profit differences of 4p per litre produced, and 2p per litre produced, in housed and grazed systems respectively, when compared to animals of average genetic merit.

Carbon accounting showed that average merit footprints across each of the dairy management regimes were significantly higher ($p<0.001$), on average by 15%. Livestock and embedded emissions were significantly higher from control merit cows ($p<0.01$). Sources of greenhouse gases varied by dairy management regime highlighting that farm mitigation may prove more effective if applied by system type. Pairwise comparison tests showed greenhouse gases to be significantly different in totals and type across the management systems. The effect of natural variation in the nutritional quality was investigated, and simulated footprints considering variation in diet digestibility and crude protein differed significantly from footprints using standard methods ($p<0.001$). Mass and economic allocation methods, and land use functional units, resulted in differences in system performance ranking. Eutrophication and acidification potentials provided impact results relating to water and air pollution and were shown to follow a similar system performance ranking as GHG emissions.

Dairy system efficiency was found to differ and depend upon model emphasis. Efficiency scores generated by pollutant focused models were wider ranging and, on average, higher for genetically improved animals within housed systems, consuming imported by-product feeds and exporting all manure. However, models which considered P as a non-renewable resource presented a tighter range of efficiency scores across all management regimes, and, did not always favour cows of improved genetics which require higher feed intakes. Divergent results arising from type of model applied generate questions concerning the importance of model emphasis and offer insight into the sustainability of P use within varied dairy management regimes.

Sensitivity and uncertainty surrounding financial and environmental measurements can be used to communicate the mutable nature of profitability and environmental outcomes. Performance rankings of the systems differed depending on modelling method, choice of indicator and functional unit, and also whether or not uncertainty of nutritional inputs were included. Trade-offs and synergies associated with the production of milk within current and possible future dairy systems can be communicated graphically in order to illuminate and communicate potential areas of focus to reduce emissions or improve efficiency. Irrespective of dairy management system, genetic selection for production has led to improvement in environmental and financial performance. Emissions from livestock and manure management can be reduced in all dairy systems and differences in emission source type should be considered when assessing mitigation potentials and strategies.

Lay summary

The science and practise of farming is changing to meet the needs of the environment and a key challenge for scientists and farmers is to increase the efficiency of food production systems. Historic progress and modern technology should be harnessed to develop novel agricultural production systems that deliver enhanced outcomes for animals and the environment, whilst at the same time being able to provide enough income to maintain farming families. This thesis is concerned with the production of milk, and to what extent diverse methods of dairy farming with high or average production UK dairy cows differ in efficiency and deliver different outcomes for farm finances and for the environment. This research is important because deep emissions cuts are required to limit global warming to 1.5°C and lower the risk of irreversible cascades of greenhouse gas emissions being released.

High production Holstein Friesians obtained an average of 4p more profit per litre compared to UK average production cows when managed in a housed system, and 2p more profit per litre compared to average production cows when managed in a grazing system. Sensitivity analysis found that obtaining greater milk yields in housed systems by relying on purchased concentrate feeds was not financially viable, especially because UK milk prices are not usually stable. Farm management decisions were shown to have a direct effect on profitability, because reproduction delays alter the lifetime production of a cow, and differing rates of replacement alter the age profile and annual production of a herd.

A range of efficiency analysis models applied in this thesis were found to generate differences in best to worst performance ranking of the dairy systems. Rock derived phosphorus (P) is a non-renewable resource as well as a potential pollutant. Models that focussed on P and its potential to pollute generated more favourable results for high production cows within housed regimes, and more specifically for cows consuming only imported by-product feeds and exporting all manure. However, models that included P as a non-renewable resource, thereby taking future generations into consideration, did not always favour cows of improved genetics which require higher feed intakes.

High production Holstein Friesians attracted lower product carbon footprints, irrespective of how the cows were managed, and UK average merit footprints were ~ 15% higher. Within the carbon footprints, GHG emission sources varied depending on the dairy management regime. Statistically significant differences in GHG emissions from arising land, livestock, and embedded in purchased feeds highlight that dairy farm mitigation measures may prove more effective if applied by management system type.

Agriculture has a role to play in the reduction of greenhouse gas emissions, however dairy system environmental accounting models are complex. Uncertainty arises from within a mathematical model calculating emissions, and from inputs that are entered into that model. Contrasting dairy feeding systems generated substantially different levels of costs mainly associated with purchased feed. When assessing carbon footprints, mass and economic calculation methods for purchased feed resulted in differences in dairy system ranking from best to worst. Statistically significant differences were found when natural variation in feed quality was investigated by considering diet digestibility and crude protein.

Methods employed to prevent global warming should not inadvertently cause other forms of pollution. Eutrophication and acidification potentials relate to water and air pollution and system comparison results followed a similar best to worst system performance ranking as carbon footprints. Animal health proxies and total land use for are presented alongside economic and environmental outcomes. The novel petal diagrams convey trade-offs and synergies associated with the production of milk from diverse genetic merit dairy within a wide range of dairy systems. The petals illuminate potential areas of focus to reduce emissions or improve efficiency.

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1 Introduction

1.1 Agriculture and the environment

Technology driven crop and animal productivity increases of approximately 2% annually, characterised the latter half of the 20th century, however food production in the 21st century needs to transform to meet environmental goals (Ludena et al., 2007; Foresight, 2011). Food security, competition for energy and resources, increasing biodiversity, reducing food waste, and managing consumer behaviour are issues and impacts surrounding this food system problem (Pretty et al., 2010). Future methods of farming will increasingly be driven by resource related concerns such as land availability, or environmental pressures, for example the need to reduce greenhouse gas (GHG) emissions and nutrient surpluses (Shukla et al., 2019). Impacts arising from livestock farming are associated with global environmental issues such as climate change (Gerber et al., 2010; Smith et al., 2014), ammonia emissions (Misselbrook et al., 2016), water pollution (Arriaga et al., 2009), soil erosion and loss of biodiversity (CEAS, 2000). Agriculture worldwide faces the challenge of producing ‘more with less’, by incorporating management practises that are economically feasible, socially and politically acceptable and do not damage the environment.

Climate change is the largest threat to the global economy (World Economic Forum, 2019), a ‘commons problem’ that can only be solved with international cooperation, however this has not yet succeeded as annual global carbon emissions continue to rise (Boden et al., 2017; Vardy et al., 2017). Concentrations of CO_2 in the atmosphere reached 414.7 ppm in 2019, up from 400 ppm in 2014, and 354 ppm in 1990 (NOAA, 2019). The Paris Agreement aims to prevent a 2°C global temperature rise whilst aspiring towards a limit of a 1.5°C increase (UNFCCC, 2015), however at current rates of emissions the global CO_2 budget to achieve a 1.5°C limit will be depleted in 8 years (Mercator Research Institute, 2020). In order to attain the 1.5°C limit, deep cuts in emissions will be required in a very short time scale.

Following the Kyoto Protocol, nations are obliged to calculate GHG emissions using methods described by the Intergovernmental Panel on Climate Change (IPCC)

(UNFCCC, 1997; Penman et al., 2006). To contribute to national emissions targets the agriculture sector needs to adopt more sustainable methods of farming, and in Scotland progress has been made through the Climate Change Act (2009). The more recent Climate Change Bill aims to reach net-zero emissions by 2045, five years before the UK as a whole. In the UK agricultural emissions have declined by 14% since 1990 and in Scotland a 25.8% decrease in GHG emissions has been achieved in the agriculture sector (DBEIS, 2019; SG, 2018). Emissions reductions have largely been achieved through decreased livestock numbers, lower N fertiliser use, and efficiency gains such as increased milk yields (Defra, 2017). System specific emission reduction measures will become increasingly important going forward, when broad brush options, such as reducing fertiliser and fuel use become exhausted and moves to a more circular economy advance. Models used to quantify GHGs are important tools to aid the understanding of mitigation pathways that lie within the intricate footprints of livestock systems (Opio et al., 2013). Impacts arising from livestock are well understood however the comparability of studies at farm level continues to be problematic (Lorenz et al., 2019). A bottom-up approach to mitigation in the agriculture sector is required, and holistic methods are needed to capture interactions and trade-offs (Kanter et al., 2018).

Formulating policies to enable deep emission cuts will require an understanding of measures appropriate for a range of production systems and trade-offs and synergies amongst indicators should be assessed. This thesis addresses knowledge gaps surrounding appropriate mitigation pathways and trade-offs within and between environmental, financial and animal health objectives for a range of dairy farm management types. This introductory chapter describes the broad multidisciplinary approach taken when appraising the performance of dairy farming systems. An evaluation of genetic merit and impacts arising from the production of milk are outlined alongside the methods applied in this thesis to measure and compare financial, environmental, and other indicators. The chapter ends with a description of the systems.

1.2 Dairy farming in the UK

Dairy products have been processed and consumed in Britain since the Neolithic era however the livestock industry needs to become more environmentally efficient to contribute to national GHG emission reductions (Charlton et al., 2019). Grasslands are important in the UK because they embody 70% of the agricultural land area, and in Scotland, grasslands, including rough grazing cover approx. 80% of the land mass, (Hopkins and Davies, 1994; Scottish Government, 2018). In 2018 UK farmers produced 15 billion litres of milk of which 6% was exported, and even though domestic consumption of liquid milk has declined by 1.4%, consumption of cheese cream and butter have increased by an average of 22% between 1998 and 2018 (Defra, 2018). The UK is self-sufficient in liquid milk production, and recorded a volume trade surplus in 2019, for the first time in over 20 years (AHDB, 2020). Whilst the global outlook indicates growth, following the removal of European quotas, high milk prices have not been sustained, and volatility persists, even though worldwide production is increasing by an average of 2.3% (IDF, 2018; AHDB, 2019).

A favourable climate for grass growth has allowed western areas of the UK to have a long tradition of milk production, and it has been among the top ten world producers for over 50 years (FAOSTAT, 2014). Transformation has characterised UK dairy farming for many years, for example over the decade to 2014 there was a reduction of 36% in the number of dairy farms from 21,616 to 13,815 and the average UK herd size on farms increased from 97 to 132 cows (AHDB, 2019a). In Scotland there are currently 180,293 dairy cows on 888 farms with an average herd size of 203 cows (Scottish Dairy Cattle Association, 2019). Decreases in farm and animal numbers, have been offset by increases in animal production, as between 2004 and 2019 average UK yields increased from 6886 to 7968 litres/cow/year (AHDB, 2019b).

Figure 1.1 highlights a fall in the national herd and an increase in dairy herd sizes, and yields. These changes may have led to modifications in feeding and housing strategies. March et al. (2014) reported that only 33% of dairy farms in Britain now graze all their cows during the summer months without any housing, while 8% were housing all milking cows all year round. A more recent estimate for Scotland reported that 15% of farms were housing all year round (Gooday et al., 2016). Inputs required, and outputs arising from varied feeding and housing management strategies differ and it is important to capture and measure trade-offs that arise from a range of indicators. Moves towards circular economies (Scottish Government, 2016) may alter these trends. Ruminants could contribute towards a circular economy by consuming non-human edible biomass and wastes, by supplying manure and by producing nutritious protein.

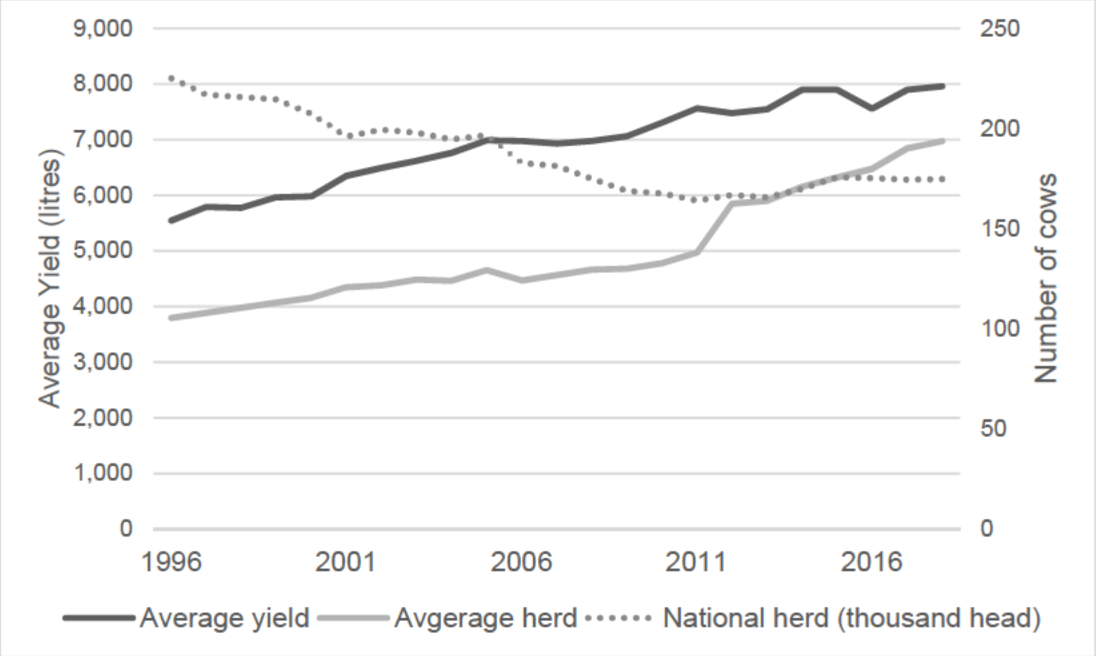


Figure 1.1 Trends in Scottish dairy cow numbers, herd size and UK average yields from 1996-2018 (AHDB, 2019a, 2019c; SDCA, 2019)

1.3 Modelling agricultural systems

Life Cycle Assessment (LCA) is a key approach to determine environmental or other impacts along a product chain by compiling an inventory of the system. LCA has the capability of evaluating effects associated with inputs and outputs stemming from production systems. The process is described by international standard ISO14040 (ISO, 2006) and follows a specific methodical framework consisting of four phases from scope and boundary setting to inventory analysis and impact assessment. Furthermore, when a system delivers greater than one product an allocation methodology can be applied and attributed to each output (ISO, 2006). Carrying out an LCA for agricultural systems can add a layer of complexity not found in industrial operations because farms often utilise multiple inputs such as natural resources, to produce multiple outputs such as milk and meat. Farming systems can be affected by temporal and spatial variations, can adopt regionally diverse management practises, and can generate considerable non-point emissions (Caffrey and Veal, 2013). Nevertheless, LCA has been successfully applied to evaluate and reduce environmental impacts from agriculture (Baldini et al., 2017). Agri-food sector case studies have advanced methodological LCA practises and fostered interdisciplinary interactions between industry stakeholders (van der Werf et al., 2014).

In order to avoid calculation complications, that can arise once products leave a farm, (for example in the dairy sector this would be associated with processing liquid milk into products such as cheese or yoghurt), a farm gate boundary can be a sufficient representation of the system (Cooper et al., 2011; Caffrey and Veal, 2013). Functional units (FU), within an LCA, can be defined as a measure of some value of the studied system from which input and output data can be normalised (ISO, 2006). Units are usually expressed as mass or volume for food (Roy et al., 2009) and other examples include land area, economic indices and nutritional values (Schau and Fet, 2008). Within dairy production, a typical FU could be related to livestock units, weight of milk solids or energy corrected milk (ECM) or land requirements (which can also be an impact category). Ross et al., (2017) highlight how choice of FU can affect perceived performance in high producing dairy systems. ECM was found to be the most appropriate FU to illuminate differences between production systems, and a dual FU was used to incorporate trade-offs between production and land use, however this did not illuminate differences between the productions systems as well as individual FU (Ross et al., 2017).

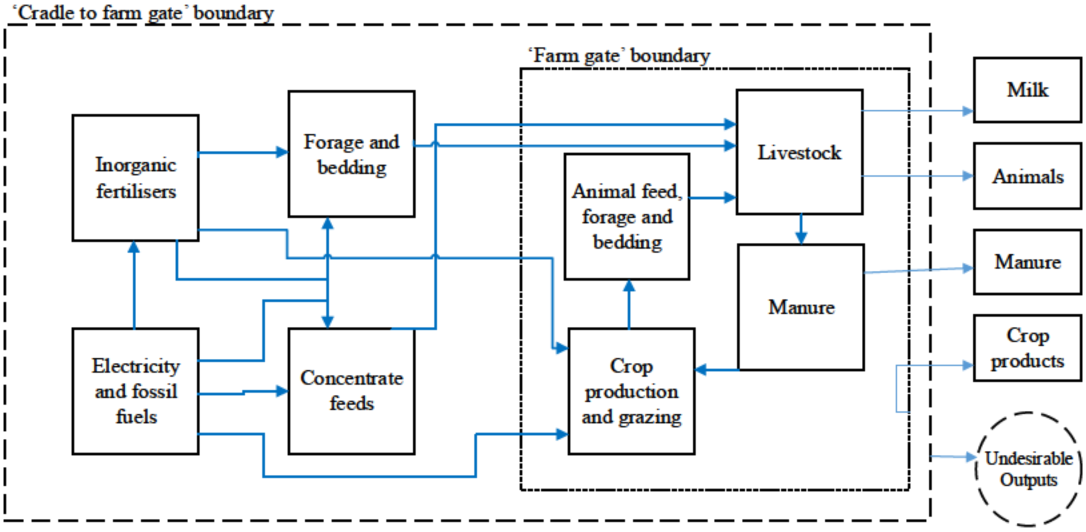


Figure 1.2 LCA boundaries applied to calculate impacts

Impact categories such as global warming or eutrophication potentials can be modelled using an annual systems inventory to capture resource use and other inputs into the system and followed by outputs leaving the farm. Figure 1.2 shows typical inputs and outputs from dairy farming and boundaries applied to calculate environmental performance in this thesis. Undesirable outputs relate to dairy system externalities and can include phosphorus surplus, GHG emissions, biodiversity loss, and nitrogen use efficiency.

A range of farm gate LCA of dairy production regimes can be found in the literature. Examples include studies that focus on evaluating the environmental impact of organic versus conventional systems (Cederberg & Mattsson, 2000; Thomassen et al., 2008). Further LCA examples include evaluations of differences between typical milk production regimes at national levels (Casey & Holden, 2005; O'Brien et al., 2014), and others focus on specific impacts such as global warming potential (Oleson et al., 2006; Ross et al., 2014). Results show higher or lower impacts from a range of milk production systems, which can vary between and within indicators. For example, organic milk production systems report lower acidification and eutrophication potentials however in some cases attract higher GHG emissions (Thommassen et al., 2008; Tuomisto et al., 2012). Farm level LCA are important tools, as they provide a method to determine trade-offs and mitigation pathways that are not apparent in national inventory GHG calculations where upstream processes such as the production of imported farm inputs are not included (IPCC, 2006; O'Brien et al., 2012). However, drawbacks can arise from differences in scope and boundaries when making comparisons of LCA and this continues to present challenges (Baldini et al., 2017).

Measures of financial, environmental and animal health performance arising from a range of dairy systems and calculated in this thesis can be related to the three pillars of sustainability. The three pillars incorporate economic, ecological and social aims and objectives, and even though sustainability is still not well defined it is often perceived using a systems approach (Goodland and Daly, 1996; Purvis et al., 2018). Sustainability can be described as an intuitive notion and one example practised since 3200BC in order to manage and maintain resources is coppicing, which maintains the life of a tree for as long as the timber is required (Coles, 1978). Within ecology, sustainability can be defined as the capacity of an ecosystem to maintain functions, productivity and biodiversity for the foreseeable future (Townsend, 2003) and an economic definition describes sustainability as being attained if capital is non-declining (Pearce, 1989) or if income is maintained (Dasgupta, 1993). A suite of financial, environmental and health performance indicators arising from novel and conventional dairy farming systems are compared in this thesis by measuring inputs and outputs of diverse milk production regimes.

Financial performance in dairying is expressed by accounting measures of income, costs and profit which are routinely used by farmers (Wilson, 2012). Impacts and undesirable outputs are gauged using an LCA approach by measurement of indicators representing environmental externalities from dairy farming such as GHG emissions, phosphorus surplus, eutrophication and acidification. Management, resource use, and animal health measures provide a further layer of performance indicators that illuminate mitigation pathways. A detailed description of indicators applied in later chapters to measure performance of the dairy systems is provided in the following sections.

1.4 Environmental performance

1.4.1 Agricultural GHG emissions

Agriculture is estimated to be responsible for 10-12% of greenhouse gas (GHG) emissions globally, with the production of milk being attributed to 2.7% (Smith et al., 2014; Gerber et al., 2010). In countries such as the UK and in Western Europe GHG emissions stemming from milk production are estimated at between 1.2 and 1.4 kg CO_2 e /kg respectively which is lower than the global average of 2.5 kg CO_2 e /kg (FAO, 2018; AHDB, 2014). A carbon dioxide equivalent (CO_2 e) is used to compare GHGs by their Global Warming Potential (GWP) relative to carbon dioxide over a given time period. GWP which is an indicator of the amount of radiative forcing or change in tropospheric energy flux caused by a substance and is measured in Watts per square metre (IPCC, 2018). GHG emissions associated with Scottish milk production were estimated to be 1.4 Mt which represented 2.5% of Scotland's total emissions reported in that year (Sheane et al., 2011). Agriculture generated 49.5Mt of CO_2e in the UK in 2009 and was the source of 40% of all methane and 76% of nitrous emissions (DECC, 2011). Figure 1.3 illustrates types and sources of GHGs that can be emitted from farming activities (IPCC, 2006 Smith et al., 2014). Figure 1.3 uses coloured arrows for the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and highlights the range of ecosystem cycles and flows driven by animals, plants, and microorganisms, as well as physical processes, that can affect fluxes of GHGs from agriculture.

Effects of anthropogenic climate change are already challenging agriculture across the globe through changes in seasonality, extreme weather and novel pests and diseases (IPCC, 2014a). Direct impacts on agriculture include reduced crop yields, crop quality, increased crop damage, and effects on the livestock sector include heat stress in animals and wider ranging pathogens (Pittelkow et al., 2014), although in some areas of higher latitude increased yields of crops such as maize and wheat have been observed (IPCC, 2019). Agricultural production is also reliant upon ecosystems to cycle nutrients and wastes, and upon insects for pollination, and climate change is adding to existing impacts such as habitat loss and soil erosion (IPCC, 2019; Cameron et al., 2014).

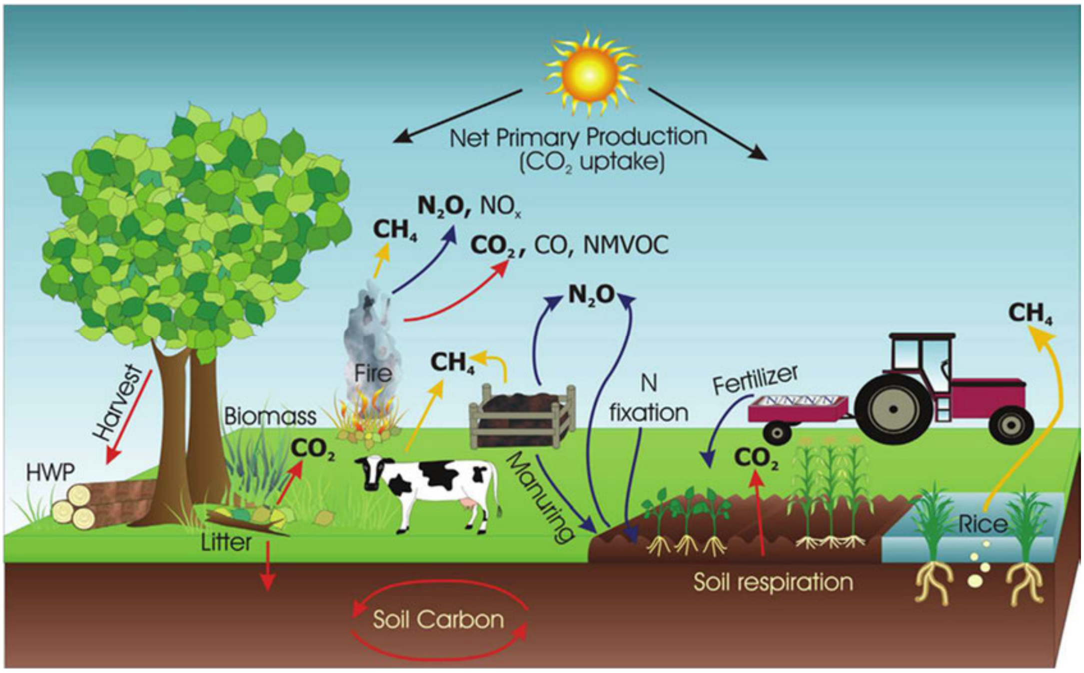


Figure 1.3 Main GHG emission sources and sinks in managed ecosystems (IPCC, 2006)

Initial mitigation of UK GHG emissions from livestock has largely arisen from a change to the Common Agriculture Policy (CAP) which ended the link between subsidies and animal numbers (DairyCo 2014, European Union, 2019). Progress continues to be made on farms through strategies such as improved nutrient management and feed efficiency promoted through the GHG Action Plan (Defra, 2017) and the Farming for a Better Climate initiative (Scottish Government, 2010). Reduction in total livestock numbers led to lower stocking densities, less fertiliser use and combined with increased yields this has led to fewer emissions generated from milk production (DairyCo, 2009). Dairy farm GHG emissions can be reduced by increasing the longevity of cows within a herd, improving their fertility and lowering initial calving age and potential has been shown for diets to be formulated with the aim of jointly reducing emissions and proportions of human edible feeds (Garnsworthy, 2004; Wilkinson and Garnsworthy, 2017). Improving digestibility of the diet through feeding additives and supplements, as well as vaccinations to reduce methane output have been proposed and Table 1.1 shows the estimated abatement potential of a range of mitigation measures that could be applied on dairy farms in the UK. Marginal abatement cost curves (MACCs) of dairy mitigation measures has shown that genetics and on farm strategies such as increasing inclusions of maize silage and improved management to be most cost effective (Eory et al., 2013; McLeod et al., 2015).

Table 1-1 Selected dairy farm mitigation measures

Greenhouse Gas	Source	Mitigation Measure	Abatement Potential
Methane	Enteric fermentation	Improved diets & forages	0.18 of CH_4 Emissions
(CH_4)		Feed additives	0.08 of CH_4 Emissions
	Manure storage	Long term management practices	0.04 of CH_4 Emissions
		Install anaerobic digester	0.96 of manure Storage
Nitrous Oxide	Fertiliser & manure	Optimal application	0.05 of N_2O emissions
(N_2O)		Grazing management /permanent pasture	~ 7 t/ha CO_2e
		Increase NUE, avoid excess N in diets	Efficiency up 10% = 6% reduction N_2O
Indirect CO_2	Farm electricity	Energy efficiency & Renewable energies	Target 40% renewable energy on farms by 2020
	Fertilisers & feeds	Use local supplies, home grown proteins	100 kg CO_2 / tonne concentrate
Direct CO_2	Farm fuels	Bio-fuels, efficient driving	0.5 of fossil fuels
All	Livestock	Lower replacement rate & sell surplus	0.11 of GHG Emissions
		Genetics & fertility	0.10 of CH_4 Emissions

GHG emissions from livestock need to be reduced at a time when demand for these commodities and absolute numbers of ruminants are increasing globally (Opio et al., 2013; Alexandratos and Bruinsma, 2012; IPCC, 2019). The IPCC (2019) calls for animal products to be sustainably produced in systems that are low carbon and resilient, alongside shifts to more plant based diets, however developments in approach and methodology over time can offer new insights and perspectives on impact and appropriate mitigation pathways. The Paris Agreement (UNFCCC, 2015) has galvanised international effort towards a target of limiting warming to between 1.5 and 2°C, however Allen et al (2018) argue that an emissions budget cannot be modelled using the standard GWP_{100} because this method does not adequately account for the temperature response from short-lived GHGs such as CH_4, which breaks down in the atmosphere after about 12 years. The other main GHGs associated with agriculture are carbon dioxide (CO_2) which remains in the atmosphere for hundreds of years, and Nitrous Oxide (N_2O) which has a lifetime of 120 years. Cain et al. (2019) point out that to achieve the Paris Agreement long-lived GHGs need to reach ‘net zero’ and any emissions offset, however short-lived CH_4 emissions should decline to stabilise concentrations however do not need to reach net zero. Allen et al (2018) and Cain et al., (2019) have developed GWP_{100} to GWP* which takes into account a larger impact of changes in rates of methane emissions and the lesser impact of stable CH_4 emission on temperature increase. Adopting a GWP* accounting method potentially has dual outcomes for the livestock because the warming effect of CH_4 can be stabilised, however the sector may be viewed as a ‘low hanging fruit’ option to deliver immediate warming reductions. This is because GWP* methods increase the sensitivity of changes in CH_4 emissions to its effect on overall global warming. GWP* could potentially be used as a lever to deliver more immediate impacts to lower warming through a reduction in livestock numbers while more difficult aspects of CO_2 mitigation are tackled. Climate change is the overarching global concern however there are other environmental issues that should be considered when applying measure to mitigate GHGs on dairy farms.

1.4.2 Phosphorus flows on dairy farms

Phosphorus (P) is both an environmental pollutant and non-renewable resource produced by a limited number of nations across the world, and, is currently described as a critical raw material (Cordell, 2010; EU, 2014). Blackwell et al. (2019) describe the uncertainty around ongoing availability of phosphorus (P) as an ‘imminent crisis’ that threatens global food security. In agriculture P supports root development and growth in grass or crop-based systems, and P is an essential nutrient for the physiology of the animal (Haygarth and Jarvis, 1999; McDonald et al., 2011). P can be imported onto a dairy farm in fertilisers, animal feedstuffs and bedding, and is exported in milk, animals or manure that leave the farm (Nousiainen et al., 2011).

A shift of focus from purely agricultural production to include environmental and health effects of farming has encouraged calls to reassess animal feeding standards for mineral needs in the UK (McDonald et al., 2011). Diets formulated to meet major nutrient requirements for high producing dairy cows within *ad lib* feeding regimes could be delivering an excess of minerals to dairy cows. Improvements in EU surface water quality have been achieved (Kristensen, 2012) through EU legislation such as the Water Framework and Nitrates Directives (EC, 2000; EC, 1991), however a lack of international consensus and legislation to account for and manage the application of phosphate fertilisers has led to an absence of common methodologies (Amon et al., 2011).

P is present in farmed soils in organic and inorganic forms, of which inorganic P represents between 70-80%, mainly in the form of phosphates of iron, calcium or aluminium depending on the soil type (Foth, 1990). Organic P is found in stable and unstable forms and up to 70% can decompose to inorganic phosphate (PO_4) annually. P moves slowly through the soil and on a dairy farm is cycled as it is taken up by crops and pasture which are ingested by cows and, if not exported in milk or meat, excess P is excreted by the animal directly onto pasture or collected, spread as slurry or farm yard manure, and P can be lost to the wider environment as run off or leaching from manure or fertilisers (Defra, 2010).

Depending on endogenous processes within each animal, stage of lactation and gestation period, a cow can absorb and excrete varying amounts of P (NRC, 2001; Guegen et al., 1988). Meta-analysis has shown that, on average, dairy cows excrete 40%, 58%, and 0.44% of P intake to milk, faeces and urine respectively (Alvarez Fuentes et al., 2016), however at certain stages of lactation up to 70% of P intake can be excreted in slurry (Ferris et al., 2010), and a linear relationship has been established between P intake and faecal output (Morse et al., 1992; Kebreab et al., 2005). Research has demonstrated that current total diet recommendation levels of 3.6-3.8 g P/kg DM are satisfactory, however in many countries levels are much higher. Recommendations as to dietary P requirements are understood (NRC, 2001) and more recently work has focussed on predicting manure volume and P excretions to allow more accurate nutrient planning and manure management at farm level (Nennich et al., 2005). Regression analysis has identified variables such as dietary P to have a significant effect on P within faeces and equations can be used to predict faecal P and milk P outputs (Klop et al., 2013). More recently, models were developed using aggregated literature to predict outputs and P utilisation from data which would be available commercially (Alvarez-Fuentes et al., 2016). Nevertheless, further research is required to fully explain output variation using further data, and variables such as stage of lactation (Klop et al., 2013).

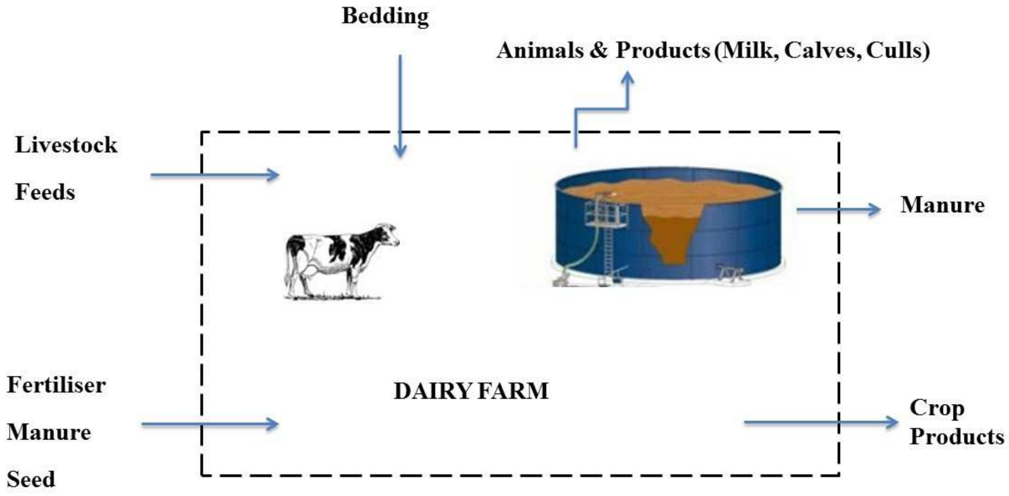


Figure 1.4 Flows of phosphorus on a dairy farm

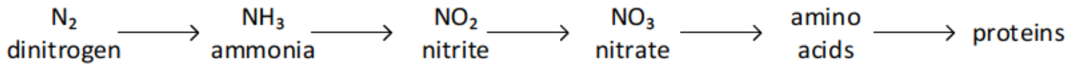
Flows of P within dairy systems can be measured by calculating a farm nutrient balance and results can reveal areas of opportunity, to lower environmental impacts, by aiming to optimize nutrient recycling and minimise negative impacts to water (Cooper and Carliell-Marquet, 2013; Mihailescu et al., 2015). A farm gate P balance can be described as a broad indicator of losses to aquatic systems and is equivalent to the OECDs gross balance, with the addition of bedding imports (Amon et al., 2011). Nutrient budgets are commonly used at farm level to assess flows (Cherry et al., 2012) and a farm gate balance is applied in Chapter 4 to identify differences in flows of P across dairy systems. A farm gate P balance can be defined as a calculation of system inputs and system outputs, where surplus is a positive difference between the total input and output of each nutrient (Figure 1.4) and this technique can also be applied to determine flows of nitrogen (N).

Before mitigation measures were introduced, P intakes in Northern Ireland were found to average 7.1g/day (Ferris et al., 2010) and in the USA dietary P is thought to be being oversupplied by as much as 160% (Wu and Ishler, 2017). Livestock numbers in the Netherlands grew post quota, increasing the national phosphate surplus and breaching an exemption allowing greater use of manure than in other EU countries. A loss of this derogation could have equated to 20% loss of the Dutch herd which is equivalent to a reduction of 480,000 animals. The Dutch government introduced phosphate reduction legislation and monetary incentives to sell cows, and P within compound feeds reduced to a maximum of 4.3g/kg. Overfeeding of this mineral is especially relevant to genetically improved animals with higher than average dry matter intakes (DMI). Legislation aimed at reducing P surplus could potentially be adopted by other nations in the future for environmental and resource security reasons.

1.4.3 Eutrophication and acidification

Nitrogen is an essential macronutrient, and in the form of dinitrogen (N_2) makes up 78% of the atmosphere on earth, however it is not directly available to most organisms in this form and lack of available nitrogen can limit a plant’s growth (O’Neill, 1993). The natural biogeochemical N cycle is complex because of the many chemical forms and reactions involving biological material, which, through the breakdown of proteins ultimately replenish dinitrogen (O’Neill, 1993). Photosynthesis capability in plant leaves is affected by N content, and inputs into farming systems in the form of fertilisers has increased crop yields and allowed greater food supplies, however losses of N from the cycling process can cause environmental problems (Evans, 1989; O’Neill, 1993; Aarts, 2003).

On dairy farms N is a key input, mainly in the form of fertilisers and feeds, and the nutrient goes through multiple transformations within the cycle (Roberts et al., 2007; Toma et al., 2013). Nitrogen in the atmosphere can be fixed by legumes, or deposited by rainwater, and uptake in mineral form by crops and pastures is ingested by livestock and the nutrient either leaves the farm as milk or meat protein and non-milk nitrogen is excreted in manure and urine directly or indirectly to the soil (O’Neill et al., 1993; Asman et al., 1998; Chagunda et al., 2009). Basic reactions in the nitrogen cycle are:



$$\underset{\text{dinitrogen}}{N_2} \longrightarrow \underset{\text{ammonia}}{NH_3} \longrightarrow \underset{\text{nitrite}}{NO_2} \longrightarrow \underset{\text{nitrate}}{NO_3} \longrightarrow \text{amino acids} \longrightarrow \text{proteins}$$

At the farm level N is cycled between plant, animal and soil pools, and a simplification of components in the cycle highlights a number of pathways where losses of N are possible (Figure 1.5). Although not shown in Figure 1.5, diverse groups of microbes are necessary engines to drive the biogeochemical N cycle and act as catalysts for oxidation and reduction reactions (Falkowski et al., 2008). Dairy farms can be a source of nutrient losses to the wider environment, mainly through livestock excretion (Erisman et al., 2007).

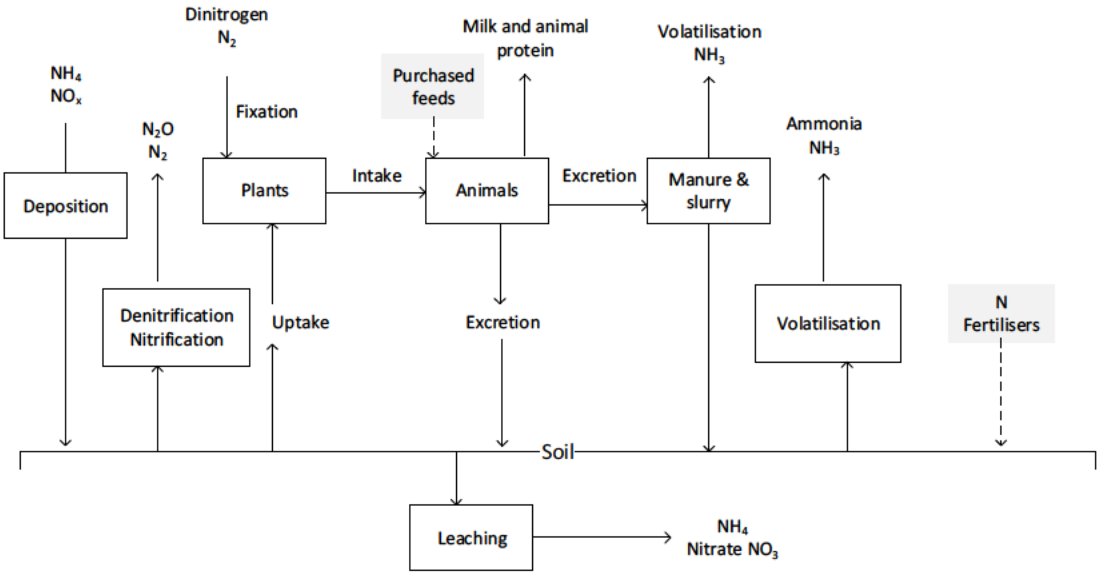


Figure 1.5 Simplified N cycling on a dairy farm (adapted from O'Neill, 1993)

Ecological impacts arising from nutrient surpluses include water pollution caused by nitrate leaching, eutrophication of surface waters, soil acidification, and plant damage from ammonia emissions (Amon et al., 2011; Erisman et al., 2007). Eutrophication refers to a state of excessive growth and decay of biomass caused by surplus nutrient inputs to soil or water which can result in oxygen depletion of a water body (O'Neill, 1993). As with the release of methane, eutrophication occurs as a natural process whereby sediments can enter lakes and rivers over time (Carpenter, 1981), however human activities can accelerate the flow through an oversupply of N and/or P nutrients to water bodies. The consequence is increased production of algae that decays with the aid of microorganisms which consume oxygen and release toxins harmful to species of animals and plants (O'Neill, 2013). As well as contributing to N_2O GHG emissions, pathways of N loss from fertilisers and manures can also contribute to ozone depletion caused by leaching of NO_3, nitric oxide (NO) and nitrite emissions from denitrification (Figure 1.5). Volatilisation of NH_3 from housed livestock, slurry storage and spreading on land can lead to acidification of soil and surface waters (Leach and Roberts, 2002). Acidification refers to a reduced pH of water and soils caused by emissions to air of NH_3, sulphur dioxide (SO_2) and nitrogen oxides (NO_x) that react with water droplets in the atmosphere and can be deposited as acid rain. In the UK fuel combustion for electricity and transport are the largest sources of NO_x and SO_2, however agriculture accounted for 87% of ammonia emissions in 2017 and the government aims to reduce emissions by 16% by 2030 (compared to 2005 levels) (Defra, 2019; Defra, 2018b). Dairy cows were attributed to 28% of NH_3 emissions which mainly stem from management of manures in storage, on land, in housing, and applications of N fertiliser (Defra, 2018b).

Methods to reduce nutrient surpluses in dairying are limited because of inefficiencies in the animal during the process of converting feed into milk as cows can excrete up to 80% of N ingested (Dewhurst and Thomas, 1992; MacDonald et al., 2011). Fermentation losses in the rumen due to poor feed conversion efficiency can lead to high excretions. Opportunities to reduce N loss in areas of a dairy system include low protein diets, improved manure management reduced fertiliser application rates through precision farming, and increasing milk yield per cow (Roberts et al., 2007). N in slurry is a valuable nutrient and losses through volatilisation can be reduced by constant manure scraping, covering storage tanks as well as optimal method and application rate (Sommer et al., 2003; Battini et al., 2014). Emissions of NH_3 can be reduced by using shallow injection or trailing shoe, when compared with standard methods of spreading. Introducing legumes into crop rotations can reduce the input of N fertilisers and help condition the soil and protect from disease (Stagnari et al., 2017).

Eutrophication potential (EP) and Acidification Potential (AP) are LCA measures calculated using inventory data and are expressed in kg NO_3 and kg SO_2 equivalents respectively (Table 1.2). EP and AP of the diverse dairy systems are measured by estimating a range of emission sources mainly stemming from fertilisers, and manure management practises. Embedded emissions arise from purchased feeds, bedding and N, P & K fertilisers and include those associated with manufacture and distribution, which in the case of the Haber process for N, can be energy intensive Volatilised and leached N and P from fertiliser applied, manure management, and manure applications and deposition at grazing also contribute to AP and EP as do pesticide and fuel use.

Table 1-2 Factors applied in the calculation of GWP, EP AP

Impact Category	Equivalent factors	
Global Warming Potential	1 kg carbon dioxide (CO2)	1 kg CO_2e
	1 kg methane (CH_4)	25 kg CO_2e
	1 kg nitrous oxide (N_2O)	298 kg CO_2e
Eutrophication Potential	1 kg nitrate (NO_3)	1 kg NO_3e
	1 kg ammonia (NH_3)	3.64 kg NO_3e
	1 kg phosphate (PO_4^{3-})	10.45 kg NO_3e
Acidification Potential	1 kg sulphur dioxide (SO_2)	1.0 kg SO_2e
	1 kg ammonia (NH_3)	1.6 kg SO_2e

Huijbregts (1999)

1.5 Measuring financial performance

As with other businesses, a farming operation can be described as the value of the outputs minus the costs of production. Profitability in dairy farming is affected by the economic environment, (milk price, feed costs, etc.) and key factors of production (land, labour, etc.) as well as the level of technical efficiency to utilize resources in an optimal manner (McCarthy et al., 2007; Kelly et al., 2012). In recent years production costs such as feed, fuel and fertilizers have tended to increase, while farm gate milk prices have not risen at the same pace (DairyCo, 2013a; Defra, 2013; Defra 2013a). The tendency for dairy farm profitability to be affected by variations in production expenditure differs depending on the relative importance of the cost component, which in-itself, will vary between production system types (Chamberlain, 2012). In the UK the main market outlet for milk is in the form of liquid (Defra, 2013) and this strong and high value UK liquid milk market has helped generate demand for an all year round supply which has consequently encouraged the expansion of more intensive systems (Alvis et al., 2012).

Benchmarking dairy systems is a common method of making financial comparison across farms, and shows feeding costs, labour, herd depreciation and power and machinery as key expenditures (DairyCo, 2014). The potential to generate profit is shown within a number of management types, regardless of herd size, or yields per cow (DairyCo, 2014). Chamberlain (2012a) evaluates benchmarked data to illustrate differences in financial performance between top and bottom producers within composite, high producing and grass based regimes and provides system specific areas of focus to improve profitability by lowering significant cost components associated with the respective management types. These studies show that as milk price drops in a volatile milk price environment the benefits associated with cost control increase. Since the abolition of the quota system in 2015, average farm gate milk price has ranged from 19.9 to 31.9 ppl (AHDB, 2019).

Globally the dairy market was estimated to value $330 billion in 2014 and more than 80% of the population consume milk or dairy products on a regular basis (FAOSTAT, 2014; FAO, 2018). UK farmers have limited ability to affect prices in a competitive market and therefore tend to focus more on controlling expenditure on inputs. Inputs such as feed costs can be determined by anticipated yields, which are affected by feed use efficiency. Genetic merit of a dairy cow can effect attributes such as biological performance (Ross et al., 2014; Roche et al., 2006), health (Ouweltjes et al., 2007), and fertility (Pollot and Coffey, 2008) which, in turn, can have a large influence on farm scale economics (McCarthy et al., 2007). In a volatile global economy, farmers producing milk should match animals within management systems that are optimal and cost effective for that genotype.

Models can provide a simplified description of key components of a farming system, interactions, and how changes in management strategy may affect the financial performance of a farm (Berentsen Giesen, 1995). The Moorepark Dairy Systems Model (MDSM) (Shalloo et al., 2004) is a stochastic budgetary simulation model which can be used to simulate a model farm. The MDSM can assess the economic effects of institutional, technical and market change at farm level and has been used to evaluate the effect different components of dairy systems. Examples include the economic and environmental effect of genetics (Shalloo et al., 2004; McCarthy et al., 2007; Ryan et al., 2011; O Brien et al., 2011) breed (Prendeville et al., 2011), system (Shalloo et al., 2004; Patton et al., 2012 and O Brien et al., 2011), and technology (Hutchinson et al., 2013).

The MDSM (Shalloo et al., 2004), was initially designed as a grass based spring calving model and was re-parameterised to encompass all-year-round calving herds as well as housed feeding systems that import concentrates and can grow multiple crops such as wheat and maize. Data from five years of SRUC dairy systems studies were utilised to simulate biological performance of the herd within the model (Pollot and Coffey, 2008). The UK MDSM integrated SRUC biological data for each genetic merit and feed system. UK prices were used to represent variable costs (fertilizer, contractor charges, medical and veterinarian fees, artificial insemination, silage, and reseeding), fixed costs (machinery maintenance and running costs, farm maintenance, car, telephone, electricity, and insurance), and prices (calf, milk, and cow) in the model (SAC, 2012; DairyCo, 2012). The UK MDSM model integrates animal inventory and valuation, milk production, feed requirements, land and labour utilization, and treats farm land as an opportunity cost, with additional land rented in when required and leased out when not required for on-farm feeding of animals.

1.6 Management, health and land use measurements

Further indicators are introduced to represent inputs and outputs of the dairy production systems that are not expressed within environmental or financial measurements. Animal health and welfare, farm management, land use and product quality can affect financial and environmental performance of dairy farms (McCarthy et al., 2007; Toma et al., 2013). Key performance indicators (KPI) are analytical tools used to provide an understanding of resource utilisation or efficiency of individual farms. KPI’s are used to benchmark farm performance by comparing results with farms utilising similar production methods in order to improve productivity and/or financial performance. When assessing impacts using LCA and a suite of performance indicators, should be considered in order to capture trade-offs.

Body condition score (BCS) measures of cow health have been shown to affect the efficiency of dairy production systems (Toma et al., 2013). BCS is a subjective measure of fat reserves which can be used as a management tool to monitor the health and productivity of the herd (Pryce et al., 2001). Body condition score (BCS) and locomotion score (LCS) can be measured on farm using 1-5 scales (Mulvanny, 1977; Manson & Leaver, 1988). Poor LCS and low BCS in dairy cows can be linked with health issues such as claw horn lesions and with reduced digital thickness (Bicalho et al., 2009). Randell et al., (2015) found a greater risk of lameness can be associated with BCS less than 2 and suggest scores of 2.5 or more may be optimal for reducing this risk. Lameness is a significant welfare issue in UK dairy herds particularly in early lactation when it can reduce milk yields and impede fertility (Kossaibati and Esslemont, 1997; Archer et al., 2010). Increased incidence of lameness can raise variable costs if cull rate increases on farm.

Age at first calving (AFC) is a KPI attributed to dairy management systems as calving patterns determine both the milk supply profile and feed requirements for cows throughout the year. AFC is also an area of the production system directly under the control of the farm manager. Financial goals associated with rearing replacement heifers can be described as minimisation of inputs whilst ensuring maximum profitable outputs (Hoffman and Funk, 1992). Reduction of inputs can be achieved by appropriate heifer nutrition and management to optimise rates of growth to achieve a lower AFC (Heinrichs et al., 2017). Delaying AFC in Holstein Friesian cows from 24 months to 36 months has been shown to increase body weight by 10% and decrease lifetime milk yield by up to approximately 3,500 kg (Dewhurst et al., 2002; Hutchison et al., 2013).

Land is a critical resource that has the dual property of being both a source and a sink of GHG emissions (IPCC, 2019). Observed land surface air temperatures continue to rise and while land use change and intensification have permitted the increased demand for food, degradation and desertification of the soil is a threat to food security (IPCC, 2019). Land use, expressed in hectares (ha), is a standard area based functional unit applied in dairy sector LCA which have measured a combination of on farm and total ha (Basset Mens et al., 2009; O'Brien et al., 2011, 2012; Ross et al., 2014). Total land requirement for a dairy system can be calculated by adding ‘on farm’ land utilised for pasture and crops to an estimation of ‘off farm’ land used for the production of imported feedstuffs and bedding. Off farm land can be calculated using economic allocation of feed components within each of the diets, using national data and Feedprint (Vellinga et al., 2013) for processed feeds. The following flow chart (Figure 1.6) shows measurements and categories of dairy system performance presented in this thesis.

Further impact categories relevant to dairy farming such as water use, measures of biodiversity and animal welfare could have been applied to assess dairy system performance. Welfare could have been gauged using precision farming tools such as accelerometers that can record animal behaviours such as lying time and numbers of steps taken, however data was not available for all cows in all years of data collection. Had assessments been carried out over the decade from 2006 to 2016 measures of farm biodiversity such as Simpsons Index for plants, could have been used to measure any effects of alternative cropping on field verges and biodiversity strips. Water is a valuable resource and measures of water intake by animals and water use on farm could also have been included, however water intake measurements commenced in 2012 and data was not available for all dairy systems.

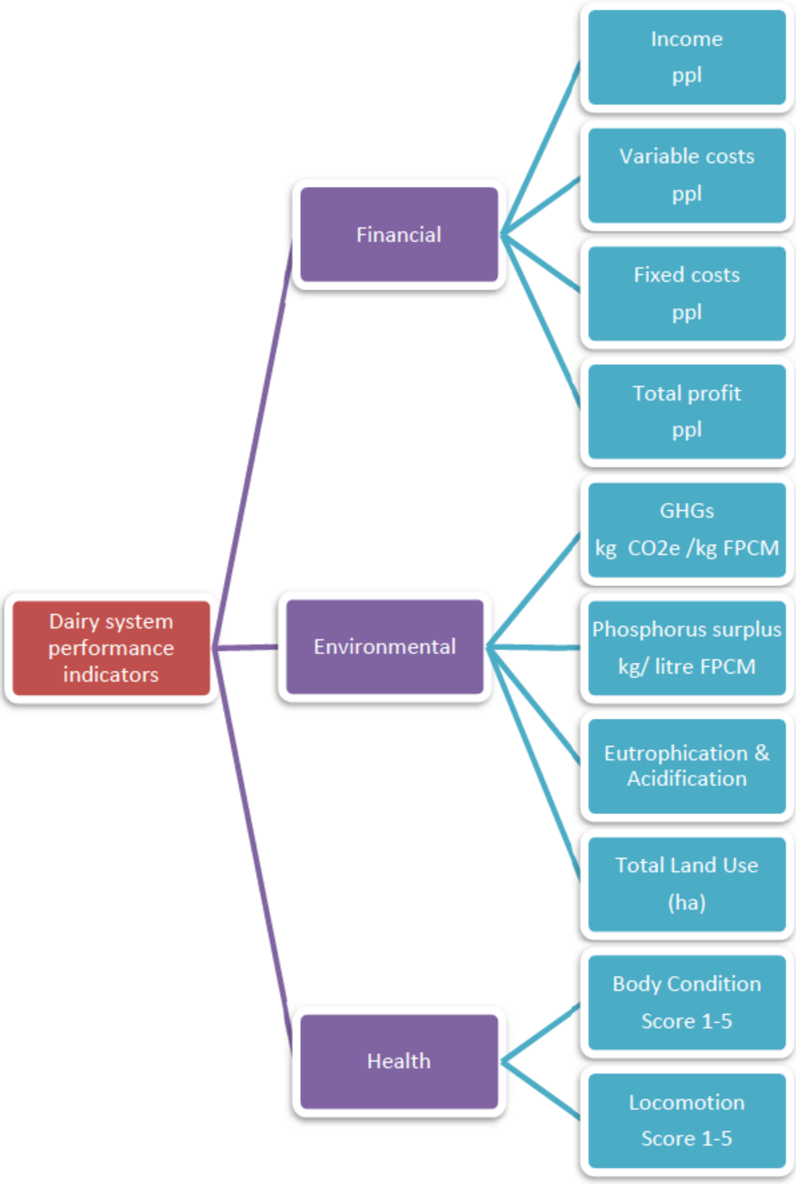


Figure 1.6 Flow chart showing indicators measurement types and units applied in this thesis to assess the performance of dairy systems

1.7 Analysis of multiple indicators

This section describes methods of analysis applied in the final chapter which utilise multiple indicators to explore comparative efficiency and performance of the dairy systems and trade-offs between outcomes. Methods used to measure indicators and quantify trade-offs across agricultural systems are central to providing a comparable holistic analysis.

1.7.1 Data envelopment analysis

Data Envelopment Analysis (DEA) is a linear programming technique stemming from operational and economic research and used to measure the efficiency of production systems (Farell, 1957; Färe et al., 1994). Application of DEA has grown in recent years (Emrouznejad et al., 2009) and it is a useful approach to measure farm efficiency because multiple inputs and outputs can be assessed and weighting is not required (Cooper et al., 2007). The method was introduced by Farrell (1957) who was interested in quantifying possible increases in output from firms brought about by improved efficiency. DEA characterises each firm as a decision-making unit (DMU) and provides a means of analysing and quantifying the extent to which DMU’s fail to optimise performance (Fare et al., 1994). Production systems such as dairy farms generate both desirable outputs (e.g. milk) and undesirable outputs (e.g. GHG emissions) and developments were made to models to include environmental externalities as undesirable outputs (Pitman, 1983).

Firms are assigned an efficiency score between zero and one, with 1 representing efficient firms which are benchmarks, operating along a best practice frontier where it is not possible to increase the production of one good without decreasing the production of another. Scores assigned to inefficient firms determine the level of improvement needed to operate efficiently and these amounts are known as slacks. Charnes, et al., (1978) developed a radial model approach, and Tone (2001) introduced a slacks-based measure (SBM) of efficiency which does not assume proportional reductions of inputs and undesirable outputs. A SBM considers the sum of all slacks within the efficiency score and undesirable outputs are modelled as outputs rather than as inputs to be minimised such as in Shortall and Barnes (2013). Several studies have applied DEA to assess the environmental efficiency of dairy farms (Bravo-Ureta and

Reiger, 1991; Iribarren et al., 2011; Kelly et al., 2012; Toma et al., 2013) however, SBM's can provide a clearer distinction between efficient and inefficient DMU's and can illuminate causes of inefficiency in the production process (Cooper et al., 2007; Soteriades et al., 2015).

The concept of disposability is introduced into the modelling process to describe the effect of reduction of undesirable outputs on both inputs and desirable outputs. Weak disposability of undesirable outputs occurs if undesirables are unable to be reduced without having to increase inputs or decrease desirable outputs. On the other hand, desirable outputs could be considered strongly disposable if gains cannot be made without incurring increased costs. Dairy farm DEA studies assign both weak (Ramilan et al., 2011; Toma et al., 2013) and strong disposability (Iribarren et al., 2011; Shortall and Barnes, 2013) to undesirable outputs. Chapters of the thesis apply DEA as a holistic method of assessing environmental efficiency of the dairy systems using models suggested by Soteriades et al., (2015) to assess dairy farms. Efficiency results are presented alongside other measures of farm performance to allow the assessment of trade-offs between system indicators.

1.7.2 The assessment of trade-offs

In order to implement practises designed to improve the sustainability of agricultural systems, both understanding and having the capacity to address trade-offs and synergies that can occur between environmental and socio-economic outcomes is required (Kanter et al., 2018). Where possible the analysis of trade-offs should take a transdisciplinary approach (Klapwijk et al., 2014) which should begin with defining indicators to aid drawing conclusions (Dale et al., 2015) and should also be applied to the communication of outcomes (Kanter et al., 2018). Assessment of trade-offs can be achieved by comparison of indicators under varied scenarios alongside methods of visualisation that effectively communicate results (Villa et al., 2014; Kanter et al., 2018). Diverse milk production system scenarios are compared in this thesis to assess trade-offs between environmental, financial, resource use and health objectives.

Conveying the trade-offs graphically is essential and can assist in the interpretation of interactions between indicators as well as highlight patterns across scenarios (Miettinen, 2014; Kanter et al., 2018). Approaches used to visualise trade-offs across agricultural indicators and scenarios range from conventional tables, bar charts, box plots and scatter plots to more innovative spider, radial and petal diagrams (Tuomisto et al., 2012; Bommarco et al., 2013; Kanter et al., 2018; Foley et al., 2011). Petal diagrams have been used, for example by Foley et al. (2005, 2011) to compare ecosystem service provision and to present an assessment of agricultural systems as measured against environmental and food security goals. Novel use of radial or flower diagrams by Steffen et al. (2015) to illustrate the impact of human activities and by Raudsepp-Hearne et al. (2010) to quantify ecosystem services across landscapes offer visually attractive techniques to illustrate trade-offs. Challenges in the communication of trade-offs include the ability to incorporate estimates of error and uncertainty for the benefit of policy makers and a need to work with stakeholders to achieve this (Miettinen, 2014; Kanter et al., 2018). Issues around gaps, oversimplification and questionable assumptions surrounding indicators have also been found and optimisation models that avoid weighting bias have been proposed (Carletto et al., 2015; Polasky et al., 2008; Groot et al., 2012). Challenges for trade-off analysis include the incorporation of market processes, a need for data alignment and improved stakeholder engagement at each stage of the modelling process (Kanter et al., 2018).

1.7.3 The Langhill experiment

Data used in this thesis originates from the Langhill herd of Holstein Friesian cows which form one of the world's longest running genetic line × feeding systems experiments. Information gleaned from the systems trials have over the last two decades informed dairy science in the fields of genetics (Veerkamp et al., 1993; Simm et al., 1994; Coffey et al., 1997), fertility (Pryce et al., 1999; Banda et al., 2013) animal health (Randall et al., 2015; Smith et al., 2016), welfare (Barrier et al., 2012), environment (Chagunda et al., 2009; Bell et al., 2010; Toma et al., 2013; Ross et al., 2014), management (Bell et al., 2007) and modelling methods (Soteriades et al., 2015). In-depth long-term recording of the Langhill herds enabled extensive and detailed information to be extracted from the database. Data was taken from cows belonging to the herd based at the SRUC's Crichton Royal Farm, Dumfries, Scotland from 2006 to 2010 and from 2012-2016 and equated to 36 system farming years. A Select (S) group of cows were sired by bulls with high predicted transmitting abilities (PTA) for fat plus protein yield with a Control (C) group sired from UK average merit bulls (Pryce et al., 1999). Cattle from the system trials were managed according to the same rules and each regime was designed to allow animals to express their potential for milk production within the limitations of the rations offered. During all the trials cows were milked thrice a day and housed in the same building with cubicles, concrete passageways and automatic scrapers. Whilst indoors cattle were fed a complete diet offered as a total mixed ration (TMR) irrespective of milk yield and stage of lactation. Sub-groups alternated, every 3 days, either between being fed through Hoko gates, (Insentec BV, Marknesse, The Netherlands) which recorded individual feed intake, or otherwise being fed as one group. Data were drawn from four distinct feeding system trials maintained between 2006 and 2016. During the first comparison (2006 – 2010) cows were given either a low forage (LF) diet consuming an average of 3.0 tons of concentrate annually or a high forage (HF) diet containing approximately 1.2 tons of concentrate (Chagunda et al., 2009). Diets for milking cows within the second comparison (2012 to 2016) either consisted solely of purchased by-products (BP) largely from food and beverage industry wastes and requiring no crop land, or solely of forage and protein crops grown exclusively from land on the farm, (HG). The BP and HG regimes can be considered novel as these diet types are unconventional and would not be routinely fed by farmers in the UK however, are not inconceivable.

Forage components fed in the complete diets fed in the LF, HF and HG system consisted of home-grown grass silage, maize silage and whole crop wheat alkalage or wheat grain. The HG forages also included lucerne, red clover silage and spring beans. Within the BP system the only non-processed feedstuff consumed was chopped straw. Fresh weight (FW) and dry matter (DM) proportions of the complete diets are provided in Table 1.3. LF and HF cows were fed 0.6 kg/day fresh weight of a standard concentrate whilst in the milking parlour. In all systems cows were dried off eight weeks prior to the estimated calving date and consumed a straw based diet, and after four weeks were fed a transition diet which consisted of 30% of the average daily dry matter intake of the appropriate milking ration for the cow group.

Table 1-3 Constituents, FW and DM proportions of rations in the feeding systems

Diets		Fresh weight	Dry weight	Propn. DM
By-product	Barley Straw	6.5	5.30	0.23
	Sugar beet pulp molasses	5.5	4.90	0.21
	Breakfast Cereal (Maize Gluten)	3.3	3.00	0.13
	Vitagold	8.0	2.20	0.09
	Biscuit Meal	2.2	2.00	0.09
	Wheat Distillers Dark Grains	2.2	2.00	0.09
	Soya Bean Meal Hipro 50%	2.2	2.00	0.09
	Molasses Cane	2.0	1.30	0.06
	Minerals (High P)	0.2	0.20	0.01
	Protected Fat Megalac	0.4	0.38	0.02
	Total	32.5	23.3	
Low Forage	Wheat Grain	4.3	3.83	0.16
	Sugar Beet Pulp Molasses	3.5	3.14	0.13
	Soya Bean Meal	3.1	2.81	0.12
	Distillers Grains (Wheat)	1.5	1.34	0.06
	Soya Hulls	0.6	0.57	0.02
	Megalac	0.3	0.33	0.01
	Sopralin & Alkcarb	0.4	0.3	0.01
	Grass Silage	19.8	6.6	0.28
	Maize Silage	8.2	2.2	0.09
	Alkalage	3.3	2.2	0.09
	Minerals/Vitamins	0.25	0.25	0.01
	Total	45.4	23.6	
High Forage	Grass Silage	17.5	9.6	0.45
	Maize Silage	12.9	3.2	0.15
	Alkalage	4.9	3.2	0.15
	Rapeseed Meal	1.7	1.5	0.07
	Barley Distillers Grains	2.5	2.3	0.11
	Wheat Distillers Grains	1.4	1.2	0.06
	Minerals/Vitamins	0.2	0.2	0.01
	Total	41.1	21.2	
Homegrown (winter ration)	Grass Silage	35.1	9.0	0.44
	Spring Beans	5.5	4.7	0.23
	Wheat Grain	4.0	3.4	0.17
	Red Clover Silage	10.0	2.0	0.10
	Maize Silage	4.0	1.0	0.05
	Lucerne silage	1.0	0.3	0.01
	Minerals/Vitamins	0.2	0.2	0.01
	Total	59.8	20.6	

Ration formulation for predicted intakes to satisfy a dairy cow of 650 kg and yielding 30 kg/day

1.7.4 Production systems

UK dairy farm management varies across the country and methods range from low input pasture systems to more intensive higher yielding confined management, as well as more conventional composite systems that adopt a mixed approach to housing and feeding (DairyCo, 2012; March *et al*., 2014).

The four dairy production systems evaluated in this analysis are:

1. A high forage (HF) composite system which can be defined in this study as a regime with grazing cows when availability of grass is adequate, and housing during inclement winter months when animals are indoors being fed conserved forage and concentrate through a total mixed ration (TMR);
2. A low forage (LF) system can be described here as management with animals housed all year round being fed a ration of conserved forage and concentrate through a TMR;
3. A home grown (HG) partially housed system is defined here as a regime where all feed is grown on the farm and no purchased feeds except minerals, where animals are housed for one period each day and fed a conserved forage TMR, cows are grazed for a maximum of two periods each day when grass is sufficient;
4. A novel by-product (BP) fully housed, landless system feeding mainly non-human edible industry by-products or co-products and no forages.

Each diet was developed to deliver appropriate levels of metabolized energy (ME) and CP for the required maintenance plus a target yield for cows within each of the genetic line × feeding systems. Feeding systems within the groups are defined here as: Low Forage Control (LFC), Low Forage Select (LFS), By-product Control (BPC), By-product Select (BPS), High Forage Control (HFC), and High Forage Select (HFS), Homegrown Control (HGC), and Homegrown Select (HGS).

All herds were managed so that calving took place all year round and each group contained approximately 50 cows being fed a total mixed ration (TMR), approx. 750g of concentrate per cow per day was given in the milking parlour within the HF and LF experiments only. The LF and BP cows were housed all year round (i.e. non-grazing), the HF and HG cows were grazed when there was sufficient available herbage. The HG cows were managed at grass for a maximum of 2 periods per day and housed for at least 1 period overnight (approx. 8hrs) whilst feeding on TMR throughout the grazing season. Cows were kept in the herd for at least 3 lactations unless welfare dictated culling the animal was necessary. In addition, cows who failed to conceive after 7 inseminations were removed from the herd.

1.8 The thesis

1.8.1 Aims and objectives

This cross-disciplinary research adds to knowledge by providing a holistically measured comparison of novel and conventional dairy farming systems using multiple indicators, a range of modelling techniques and a novel visual representation of milk production scenarios. Trade-offs and synergies associated with the production of milk within current and possible future dairy systems are assessed to enable mitigation of undesirable outputs and improvements in system efficiency. Aims are to determine and describe differences in profitability, health, resource use and environmental performance arising from two genotypes of Holstein Friesian cows managed within housed, grazed and novel UK dairy systems.

Indicators stemming from the dairy systems are calculated with an LCA approach using a ‘cradle to farm gate’ boundary. Comparative efficiency analysis and the assessment of trade-offs are untaken to provide knowledge for farmers and decision makers on mitigation pathways appropriate for diverse genotypes of dairy cows in a range of feeding and housing management regimes. This thesis is broad in overall scope, through the assessment of indicators that cross disciplines, however measurements and methods employ fine detail and novel modelling techniques. Results from Chapter 2 to Chapter 5 focus on a particular environmental or financial comparison. Chapter 6 centres on drawing together results from previous chapters and presenting a visual comparison of multiple outputs that easily communicates comparative system performance, from a wide range of indicators

The thesis is founded on the concept of enabling movements towards more sustainable methods of milk production across a range of farm management methods, by highlighting trade-offs across indicator types and alternative mitigation pathways depending on dairy system type. Objectives addressed within the thesis centre around cross-disciplinary measurements of dairy farm performance which consider uncertainty surrounding calculation methods, or the sensitivity of the indicator to change, which are addressed in the following order:

1. Assess the effect of genetic line, feeding system and replacement rate on production, costs, income and profitability
2. Assess the effect of genetic line and feeding system on the environmental performance of milk production systems
3. Examine, the comparative efficiency of multiple dairy systems and present an assessment of trade-offs.

The findings from each the objectives listed above form the structure of the thesis and are presented in Chapters 2 to 6. Objective 1 is addressed in Chapters 2 and 3 which describe differences in profitability of the herds, the effect of changes in milk price and feed costs, and the effect of changes in management techniques such as replacement rate. Financial performance results presented in Chapter 2 are published in Livestock Science (March et al., 2017). The second objective is tackled in Chapters 4, 5 and 6 which focus on environmental outputs through flows of phosphorus across the systems, carbon footprinting and eutrophication and acidification potential. The final objective is described in Chapter 6 which draws results from preceding chapters. Results presented in Chapter 4 are published in Ecological Indicators (March et al., 2016). Copies of publications are provided in the Appendices alongside peer reviewed conference proceedings. The following chapters of this thesis make use of fine detailed data to compare the performance of the dairy farming systems from multiple perspectives. Financial performance is the focus of the next two chapters and environmental performance considering phosphorus, GHGs, acidification and eutrophication potentials is assessed. Land use and health indicators are then presented alongside environmental and financial indicators to visualise and assess trade-offs.

Chapter 2

2 Financial performance of composite and housed dairy production systems

2.1 Summary

Milk production in a volatile global economy requires matching suitable genotypes within efficient regimes to deliver optimal and cost effective dairy farming systems. This chapter determines and describes differences in profitability between the two genetic merits of Holstein Friesian cows managed within contrasting systems. Economic analysis is carried out by application of Moorepark Dairy Systems Model simulations. Scenarios explore profitability differences between the management types when applied to a fixed herd size of 200 cows and a limited land availability of 80ha. Sensitivity analysis describes the economic effect of changes in both feed costs and milk price. Results illustrate benefits within each dairy system depending on available resources, and show considerable differences in inputs, outputs, costs and profitability of each of the management types. On average, animals of an improved genetic merit achieve 4p more profit for every litre produced than those average merit cows in a housed system, and 2p more within composite systems. Average genetic merit cows consuming a high forage diet plus grazing can be profitable however losses are made when this genotype is confined and fed high levels of concentrates. Differences in profitability brought about by improving replacement rate and age at first calving (AFC) are further objectives explored in this chapter. Reducing replacement rate by 1% in a herd of improved merit Holstein Friesian cows could increase profits by up to 0.3p/l in a housed system and by 0.43p/l in a composite system.

2.2 Introduction

Financial success in farming, as with other businesses, can be described as the value of the outputs minus the costs of production. The profitability of a dairy farm is determined by the economic environment, (milk price, feed costs, etc.) as well as the relative availability of the key factors of production (land, labour, etc.) and the level of technical efficiency to utilize resources efficiently (McCarthy et al., 2007; Kelly et al., 2012). More recently production costs such as feed, fuel and fertilizers have tended to increase, while farm gate milk prices have not risen at the same pace (DairyCo, 2013a; Defra, 2013; Defra 2013a). Wilson (2011) provides detailed net margin analyses of farms in England, and demonstrates that wide ranging performance found across the dairy sector can largely be explained by differences in yields, labour use, and milk price, and he recommends further investigation by clustering data into management groups.

Due to a favourable climate for forage growth, the UK has a long tradition of milk production and has been among the top ten world producers for over 50 years (FAOSTAT, 2014). While the country is currently self-sufficient in liquid milk, it is anticipated that production increases necessary to fully supply domestic requirements by 2020 correspond to 5-6 billion litres of additional milk. Additional milk produced, could come from a combination of new entrant dairy farmers, increased cow numbers on existing farms, as well as a continued rise in average milk yield per cow at farm level. UK dairy farming can be characterised by a broad array of production methods that range from low input grazing to more intensive higher yielding confined systems, as well as more conventional composite systems that adopt a varied [approach] to housing and feeding (DairyCo, 2012). All year-round production results in a “flat” milk supply profile as processors are able to maximize their production capacity (Geary et al., 2013) however there are implications in relation to calving system and ultimately costs of production. To compete in a global economy, with anticipated milk price volatility, production systems need to be efficient regardless of the level of scale (Dillon et al., 2008).

The tendency for dairy farm profitability to be affected by variations in production expenditure differs depending on the relative importance of the cost component which in itself will vary between production system types (Chamberlain, 2012). Benchmarking of UK dairy systems highlights feeding costs, labour, herd depreciation and power and machinery as key expenditures, and shows the potential for profit within each management type regardless of herd size, or yields per cow (DairyCo, 2014). Chamberlain (2012a) evaluates the benchmarked data to illustrate differences in financial performance between top and bottom producers within composite, high producing and grass based regimes and provides system specific areas of focus to improve profitability by lowering significant cost components associated with the respective management types. These studies show that as milk price drops in a volatile milk price environment that the benefits associated with cost control increase. Potential effects on profitability within the systems, stemming from differences in genetic merit, are not included in the benchmarking analysis.

Genetic merit of Holstein Friesian dairy cow can effect attributes such as biological performance (Ross et al., 2015; Roche et al., 2006), health (Ouweltjes et al., 2007), and fertility (Pollot and Coffey, 2008) which have a large influence on farm scale economics (McCarthy et al., 2007). Within pasture based dairy management, the production and profitability effects of feeding system (FS), genotype of Holstein Friesian, and their interactions is well researched (Horan et al., 2004; McCarthy et al., 2007). The objective of this research is to determine and describe differences in profitability between two divergent genotypes of Holstein Friesian cows within housed and composite systems by application of the Moorepark Dairy Systems Model with Langhill herd data and to investigate differences in profitability brought about by changes in replacement rate and age at first calving.

2.3 Methods

The Moorepark Dairy Systems Model (MDSM) (Shalloo et al., 2004), is used to assess the economic effects of institutional, technical and market change at farm level and in the past has been used to evaluate the effect different components of grass based dairy systems. Some examples include the economic and environmental effect of genetics (Shalloo et al., 2004; Ryan et al., 2011; O Brien et al., 2011) breed (Prendiville et al., 2011), system (Patton et al., 2012) and technology (Hutchinson et al., 2013). Production data for this exercise was gathered from the Langhill dairy systems experiment, lasting 5 years and farming with two divergent genotypes of Holstein Friesian cows fed on contrasting diets (Chagunda, 2009). The experiment was carried out at SRUC’s Crichton Royal Farm, in Dumfries, Scotland which is located on a silty loam soil. Recent examples of the application of Langhill data illustrating environmental and health effects of dairy systems include (Toma et al., 2013; Ross et al., 2014; Randall et al., 2015).

2.3.1 Dairy systems description

Herd production data was used to model the economic performance of each system, focussing on the interaction between genotypes and feeding systems. The herds are comprised of two contrasting genetic lines, one selected for increased production of milk fat plus crude protein (CP) yield, the Select line (S) which represents the top 5% of UK genetics and the Control line (C) which corresponds to the UK average genetics. On average the herd will [contain] approximately 50 experimental cows, calving all year round were equally allocated to a low forage (LF) diet within a confined system or a high forage (HF) diet in a composite system where cows were turned out in spring and grazed on average for 163 (+/- 13) days within a rotational grazing system when grass available was sufficient. Cows were fed the respective diets as a total mixed ration (TMR). In addition cows received concentrate in the milking parlour with the HF group being fed a TMR during the winter months and pasture in summer and the LF group fed TMR all year round. Table 2.1 shows average concentrate and forage dietary inputs, milk production, milk composition, live weight, and reproductive performance data between 2006 and 2010

Table 2-1 Key production values applied in the MDSM

	Production System [a]			
Characteristic [b]	HFC	HFS	LFC	LFS
Average milk yield, kg/cow	6833	7575	8824	10553
Fat yield per cow, g/kg	38.1	40.1	36.2	38.7
Protein yield per cow, g/kg	31.5	32.9	30.8	33.1
Lactose yield per cow, g/kg	43.5	43.1	43.1	43.0
Butterfat, %	3.81	4.01	3.62	3.87
Protein, %	3.15	3.29	3.08	3.31
Milk solids, kg/ cow	475	553	591	757
Average Weight, kg/cow	580	608	614	625
Replacement rate %	30	32	30	32
Total services per cow	2.50	2.50	2.50	2.50
Total kg grazed grass per cow	1650	1815	0	0
Total kg DM silage per cow	2173	2311	2085	2353
Total kg DM maize per cow	678	723	623	709
Total kg DM alkalage per cow	678	723	415	472
Total kg DM concentrate per cow	1288	1334	3813	4309

[a] HFC=High Forage Control, HFS=High Forage Select, LFC=Low Forage Control, LFS=Low Forage Select

[b] DM = dry matter

Milk yield and milk composition for genotypes within feed systems were modelled for an average group for each month of calving rather than for individual cows. Cows were milked thrice daily and yields and milk composition were measured weekly. The systems were designed to allow each genotype to express its potential within each feed system largely unrestricted by limitations in feed supply. The ratios of feeds in the diets for the different systems were not influenced by milk yield, but the amount of feed offered was altered to meet the Net Energy (NE) of the system (Jarrige, 1989). The NE content of concentrate was determined using the feed unit for lactation (UFL) content of the ingredients (O'Mara, 1996). The NE values of the different feed stuffs were related to the *in vitro* DM digestibility whilst the NE content of the herbage was related to its chemical composition (Jarrige, 1989). Feed requirements evaluated from Langhill data were calculated using the MDSM to meet the net energy requirements for maintenance, milk production, pregnancy and body weight change across lactation (Jarrige, 1989) and were subsequently validated against the recorded data. Total concentrate DM intake averages derived from FS intake data were 3,572, 4,017, 1,209 and 1,272 kg respectively for the LFC, LFS, HFC and HFS groups respectively.

The proportion of cows removed from each herd comprised of cows that failed to become pregnant, as well as voluntary culling and cow mortality. Average calving intervals for the LFC, LFS, HFC, and HFS groups were 395, 411, 401 and 406 days respectively. For this analysis, parity structure was calculated to be representative of an actual replacement rate due to involuntary culling rate plus 10% of the remaining herd which were culled for voluntary reasons (Hutchinson et al., 2013). Actual parity structure in lactations 1,2 and 3+ was 38%, 27%, 35% and 38%, 32%, 30% for HFC and HFS groups respectively. Within the housed LF system the distribution of cows within lactations 1-3+ was 48%, 26%, 26% for S cows and 38%, 31%, 31% for C cows respectively. All replacements were brought onto the farm and rates used in the simulation of 30% and 32% for the C and S genotypes were comparable to DairyCo Milkbench average replacement rates for herds with similar production characteristics (DairyCo, 2012). Herd replacement rates from the systems study were not applied because the experimental protocol dictates that all milking cows remain in the experiment irrespective of production outcomes and exit the experimental herd after their third lactation as long as a replacement heifer is available.

Table 2-2 Assumptions applied in the MDSM for Select and Control genotypes of Holstein-Friesian cows managed under a High or Low Forage feed system.

Item [b]	Production System [a]			
	HFC	HFS	LFC	LFS
Replacement heifer price, £	1,300	1,300	1,300	1,300
Labour, hrs/cow/year	34.1	34.0	32.4	32.2
Milk price, ppl £	0.30	0.30	0.30	0.30
Average culled cow price, £/cow	306	321	324	330
Average male calf price, £/calf	74	73	74	73
Concentrate cost fresh weight, £/tonne	275	275	303	303
Silage cost, £/tonne DM	100	100	100	100
Maize cost, £/tonne DM	116	116	116	116
Alkalage cost, £/tonne DM	110	110	110	110
Maize yield, DM/ha	10.2	10.2	10.2	10.2
Alkalage yield, DM/ha	11.0	11.0	11.0	11.0
Opportunity land cost, £/ ha	272	272	272	272

[a] HFC=High Forage Control, HFS=High Forage Select, LFC=Low Forage Control, LFS=Low Forage Select, [b] DM = dry matter

2.3.2 Moorepark Dairy Systems Model (MDSM)

The MDSM integrates animal inventory and valuation, milk production, feed requirements, land and labour utilization, with an economic analysis. Land area was treated as an opportunity cost, with additional land rented in when required and leased out when not required for on-farm feeding of animals. Variable costs (fertilizer, contractor charges and veterinarian fees, artificial insemination, silage, and reseeding), fixed costs (machinery maintenance and running costs, farm maintenance, car, telephone, electricity, and insurance), and expenses were based on current prices (SAC 2012; DairyCo 2012). Table 2.2 shows cost assumptions applied in the MDSM for each production system.

2.3.3 Parameters for economic comparison

Labour costs included in the analysis were £37,500 per year (£15.00 per hour) for the first labour unit which represented the labour associated with management. Additional labour unit's required for a general operative were priced at £25,000 per year (£10.00 per hour), based on standard industry average estimates for skilled agricultural labour (UK Government, 2013). One labour unit is defined as at least 2500 hours worked on the farm by a person over 18 years of age (DairyCo 2010; UK Government, 2013). The tasks within each system consisted of, milking and parlour washing, cow and calf care, grassland management, animal health, cleaning and miscellaneous. The time allocated to the different tasks was based on average labour estimates from O' Donovan (2000); O'Brien et al. (2002 and 2007), and DairyCo (2010) and milking related labour increased by 33% as the number of milkings per cow per day increased from 2 to 3.

Forage production per hectare was estimated at 10 t of DM for pasture and grass silage in all systems (Bell et al., 2011) and herbage utilization was set at 84%. Purchased grass silage was valued at £100 t of DM. Maize silage and ammonia-treated wheat silage annual production was estimated at 10.2 t of DM / ha, and 11 t of DM / ha respectively (Bell et al., 2011) and was included at a cost of £116 and £110 t of DM when purchased onto the farm, respectively (SAC 2012; DairyCo 2012). Machinery and contracting costs were differentiated between FS based on the operations which took place on the farm.

Whilst housed, the HF and LF FS's were fed different proportions of ingredient in the TMR. The TMR was mixed and administered by contractors using a diet feeder to feed the average number of cows housed. The diet feeder capacity and feed output assumptions were based on one feeder administering feed for 200 cows in one hour. All slurry produced while cows were housed was applied by contractor and costs for slurry application were £35/hour with a spreading capacity of $19.8m^3$ per hour. All male and female calves were sold at 1 month of age. The value of male Holstein Friesian calves was £60, the value of male and female beef breed calves was £200 and £150 respectively based on average market prices. Irrespective of genotype, all female calves were assumed sold for £250 with replacement heifers for both genotypes bought at market values of £1,300 throughout the year. The herds were bedded on sawdust, all year round for cows within the LF system, and in the winter months only for the HF herds. Profitable lifetime index (PLI) values for the LFS, HFS, LFC and HFC herds averaged 58.0, 57.3, -38.0, and -40.8 respectively.

The price schedule applied here was based on a typical UK liquid milk purchasing arrangement that comprises of a base value with bonuses and penalties. Bonus payments and penalties were implemented when milk constituents or hygienic quality deviated above and below a threshold, which was 37.0 g/kg of butterfat, and 30.0 g/kg of protein for composition. Payments for hygienic quality were penalized when mean bactoscan was >100,000 and somatic cell counts were greater than 325,000. A volume bonus derived from production scale added a minimum of 0.2p/l to daily total deliveries of between 900 and 999 litres and increased up to a maximum bonus of 3.2p/l at daily totals of between 20,000 and 24,999 litres.

2.3.4 Scenarios and sensitivity analysis

Two scenarios were simulated which centred on cows or land being limiting factors at farm level. In Scenario 1 (S1) land availability was limited to 80 ha and cow numbers were adjusted with the relationship between feed supply and feed demand while fully utilizing the land area. In Scenario 2 (S2) herd size was fixed at 200 cows and land area was adjusted to meet the feed requirements. All systems had the same pricing structure and a base milk price of 30p/l (MP1). Fresh weight purchased concentrate price was £275/T for the HF system, while the LF concentrate was 10% more expensive to take account of the higher specification concentrate used in this system. Land not utilized by the dairy system was leased out at £272 per hectare. Sensitivity analysis was undertaken to investigate the economic implications of feed and milk price volatility on overall profitability. Milk prices included in the sensitivity analysis were set at 25 p/l and 35p/l to represent a low (MP2), and high (MP3) milk price respectively and were similar to historic variations in milk price in the UK. For concentrate price, increases and decreases of 10% were applied to the base price of £275/T in CP2 and CP3 respectively and it was assumed that all production related variables were maintained as in CP1.

2.4 Results

Key herd output parameters and overall farm profitability from the simulated farm for the two genotypes managed on the different FS’s in S1 and S2 are presented in Table 2.3 and Table 2.4.

2.4.1 Scenario 1 - Land Area 80ha

Constraining available land allowed herd numbers in the different FS’s to vary based on their production demands and the capacity of the available land to meet those demands. The only feed stuff grown on the farm was grass, producing grazed grass and grass silage. All other forages and feed stuff's were purchased onto the farm which allowed the land available to be fully utilized for grass production. Due to the quantities of alternative forages and imported concentrate feeds, the LF FS was capable of carrying approximately double the number of cows than the HF FS. As genotype changed from C to S, the number of cows maintained within each system reduced by approximately 10%, because greater yields from the S genotype occur in conjunction with a higher demand for feed. Variations in herd size resulted in production output differences between feed system, the LF system averaged 3,886,441 kg of milk, whereas the HF system averaged 1,417,064 kg.

2.4.1.1 Scenario 1 - Receipts

Average milk returns were £1,263,307 and £458,424, for the LF and HF FS respectively as the LF system produced 64% more milk volume than the HF FS while utilizing the same area of land. Within each FS the highest milk sales stemmed from the S genotype which generated 8% more income from milk sales than the C genotype in the LF FS and 4% more income than C genotype in the HF FS. Differences in the number of cows managed within each FS affected livestock sales and the number of replacements required. Total livestock sales ranged from £48,527 to £119,293 as the number of cows increased with sales for the LF FS to nearly double those of the HF FS. On a per cow basis the livestock sales averaged £245 for the C genotype and £254 for the S genotype. Within each FS, the S genotype had 3% greater income from cull cow sales due to the extra bodyweight and numbers culled. The 2% lower replacement rate of the C genotype attracted 1% more in calf sale values because a greater number of higher value calves were sold from C merit systems. Livestock sales ranged from 2.8 p/l to 4.1p/l (average 3.5p/l per system), which varied due to volume of milk produced and value of the livestock sold.

Table 2-3 y outputs for Scenario 1 (S1) at a milk price of 30ppl for the Select and Control genotypes managed under Low and High Forage feed systems.

Variable	Production System [a]			
	HFC	HFS	LFC	LFS
Farm area, ha	80	80	80	80
Total land required, ha	80	80	80	80
Livestock (incl. young stock)	231	215	482	430
Cows calving	206	190	429	380
Stocking rate, cows/ha	2.88	2.69	6.02	5.38
Milk produced, kg	1,399,634	1,434,494	3,773,992	3,998,890
Milk sales, kg	1,372,792	1,409,480	3,717,945	3,948,838
Fat sales, kg	52,261	56,502	134,493	152,658
Protein sales, kg	43,181	46,374	114,514	130,536
Milk returns, £	449,850	466,997	1,213,671	1,312,943
Livestock sales, £	55,951	54,311	119,293	109,845
Replacement costs, £	89,154	89,927	178,390	187,770
Total labour costs, £	89,390	84,568	187,113	168,820
Total fixed costs, £	139,802	132,800	281,291	256,275
Concentrate costs, p/l	0.065	0.061	0.163	0.154
Total feed costs, p/l	0.12	0.11	0.20	0.19
Total costs, £	502,753	483,002	1,448,077	1,387,958
Margin per cow, £	53.5	215.9	-239	77
Margin per litre, p/l	0.009	0.032	-0.031	0.008
Total profit, £	12,327	46,404	-115,112	32,993

[a] HFC=High Forage Control, HFS=High Forage Select, LFC=Low Forage Control, LFS=Low Forage Select.

When all bonuses and penalties were included, total milk price received was 33.8, 34.1, 33.6 and 34.2 p/l for HFC, HFS, LFC and LFS systems respectively. Milk price bonuses constituted 3.9p/l on average for both the HF and LF FS's, because the HF systems received less bonus for volume, but more for fat, protein, and seasonal adjustments. The LFC system receives significantly less for non-volume bonuses and this brought down LFS. The C and S genotype received a mean milk price bonus of 3.7p/l and 4.2p/l respectively. The largest proportion of the milk payment bonus received by the HF and LF FS was for milk volume, which consisted of a bonus of approximately 2.5 and 3.0 p/l for the HF and LF FS respectively. No penalties were incurred for poor hygienic quality in this study.

2.4.1.2 Scenario 1- Costs

In a fixed land scenario, contrasting feed systems generated substantially different levels of costs with the main differences in these costs associated with purchased feed. The LF FS attracted the highest total feed costs due to the inclusion of more purchased feeds in the diet. However, in both FS's the S genotype attracted lower feed costs per litre because these animals produced an average of 20% additional milk per cow. Total feed costs were 12.0, 11.4, 20.0, 18.9 p/l for the HFC, HFS, LFC and LFS, respectively. On a per cow basis, a 2% higher replacement rate for the S genotype compared to the C genotype gave rise to an additional 4% total replacement costs. However, HF replacement costs averaged 6.3p/l whereas the LF replacements averaged 4.7p/l due to a dilution effect.

In S1, average total labour cost for the FS's were £117,642 and ranged from 3.5 to 6.4p/l depending on the FS and volume of milk produced. The LFS FS attracted the lowest per litre labour costs 3.5 p/l due to the greater volume of milk produced. However average total labour costs of £148,305 within the LF FS's were much higher than the average labour costs within the HF FS's of £86,979. Fixed costs for S1 varied with the volume of milk produced and ranged from 6.5 to 10.0p/l with differences arising from dilution effects. All systems were viewed to have similar farm infrastructure per cow but there were higher levels of cow places where cow numbers were larger. Total depreciation plus power and machinery costs averaged 6.5 and 5.0p/l for the HF and LF FS's, respectively. Total costs of production for the different systems were, 35.9, 33.6, 38.9, and 35.1p/l for the HFC, HFS, LFC and LFS systems, respectively. The LFC system had the highest total production costs (p/l) of all systems and the S genotype total production costs were on average 8% less than the C genotype due to the greater volume of milk produced.

2.4.1.3 Scenario 1 - Profit

In S1, utilizing all of the land available within contrasting systems of dairy production generated distinctly different total profits or losses within the different systems. The total profit for the different systems was £12,327, £46,404, -£115,112, and £32,993 for the HFC, HFS, LFC and LFS, respectively. The most profitable system on a total farm basis was HFS which generated 40% more profit than LFS with 50% fewer animals and 65% less milk. The LFS system produced 6% more milk volume than LFC with 11% fewer cows in the herd. Within the HF system the S herd produced 2.5% more volume and generated 270% more profit with 7% fewer cows when compared to the C herd. In S1 the total profit was 1.0, 3.0, -3.1, and 0.8p/l, for the HFC, HFS, LFC and LFS, respectively.

2.4.2 Scenario 2– Fixed Herd Size

In S2, each dairy herd size was set at 200 cows per system which resulted in the HF and LF systems not requiring the entire 80 ha of land for production. The land area required by each FS in S2 was 69, 74, 33, and 37 ha for the HFC, HFS, LFC, and LFS groups respectively and any land which was not required was leased out. Maintaining a fixed herd size resulted in lower production output differences between feed systems. Output ranged from 1,213,907 kg from the HFC system, to 1,859,949 kg for the LFS system.

2.4.2.1 Scenario 2 - Receipts

As in S1, the highest milk sales stemmed from the LFS system which attracted approximately 21% higher milk returns than LFC. Average milk sales were £411,405 and £551,228 for the HF and LF FS's respectively and on average, when including both genotypes, the LF FS generated 34% more milk sales than the HF FS, from the same number of cows. Within the HF FS the S genotype produced 10% more volume and generated 12% more income from milk sales than the C genotype, from the same number of cows. With fixed herd sizes, replacement rates and cow live-weight affected livestock sales, which ranged from £48,527 to £51,091 for the different systems, with the S genotype having the greatest livestock sales.

Based on the pricing structure, the average milk price received was 33.0p/l, with a range of +- 0.3p/l. The average milk price bonus received per system was 3.0p/l. As in S1, the greatest proportion of the milk price bonus received in S2 was based on increased volume supplied, with all systems receiving between 2.4p/l, to 2.7p/l with the remaining bonuses and penalties implemented for milk composition and supply profile adjustment.

Table 2-4 Key outputs for Scenario 2 (S2) at a milk price of 30ppl for the Select and Control genotypes managed under Low and High Forage feed systems.

Variable	Production System [a]			
	HFC	HFS	LFC	LFS
Farm area, ha	80	80	80	80
Total ha used	69	74	33	37
Livestock (incl. young stock)	200	200	200	200
Cows calving	178	177	178	177
Stocking rate, cows/ha	2.88	2.69	6.02	5.38
Milk produced, kg	1,213,907	1,335,034	1,567,598	1,859,949
Milk sales, kg	1,190,627	1,311,754	1,544,318	1,836,669
Fat sales, kg	45,326	52,585	55,864	71,004
Protein sales, kg	37,451	43,159	47,566	60,714
Milk returns, £	388,966	433,845	498,326	604,251
Livestock sales, £	48,527	50,545	49,551	51,091
Replacement costs, £	77,994	82,972	77,994	82,972
Total labour costs, £	80,798	80,412	77,223	76,830
Total feed costs, p/l	0.12	0.11	0.20	0.19
Concentrate costs, p/l	0.065	0.061	0.163	0.154
Total fixed costs, £	126,236	126,197	123,881	124,425
Total costs, £	430,086	442,048	590,558	633,366
Margin per cow, £	31.8	203.9	-214.1	104.8
Margin per litre, p/l	0.005	0.031	-0.027	0.011
Total profit, £	6,354	40,776	-42,812	20,957

[a] HFC=High Forage Control, HFS=High Forage Select, LFC=Low Forage Control, LFS=Low Forage Select.

2.4.2.2 Scenario 2 - Costs

In S2, the main differences in costs were associated with replacement rates and purchased feed, which had an effect of genotype and feed system. Even though all systems had equal cow numbers there was a wide range of costs associated with the different systems depending on the level of production. Total feed costs ranged from £145,603 to £349,360 with feed costs representing between 38% and 60% of total production costs. Feed costs were 12.0p/l and 19.0p/l for the HF and LF FS respectively.

In S2, total labour costs for the different FS's were comparable at £76,830, £77,223, £80,412 and £80,798 for LFS, LFC, HFS and HFC respectively. Total labour costs range between 4.1p/l to 6.7p/l depending on the volume of milk produced. All other variable cost differences were mainly related to the level of production which increased as the input per cow increased. Fixed costs for S2 ranged from 6.7 to 10.4p/l as the volume of milk produced changed. The total cost of production for the different systems was 31.4, 29.5, 33.4, and 31.4p/l for the HFC, HFS, LFC and LFS systems respectively. Within the S genotype total production costs were 8% less than the C genotype in the LF system and 3% less in the HF system due to the greater volumes of milk produced, while the LF FS total production costs (p/l) were on average 5% more than the HF FS.

2.4.2.3 Scenario 2 - Profits

In S2, a fixed number of cows within contrasting systems of dairy production generated a wide range of total profits or losses. In S2, the total profit for the different systems ranged from a profit of £40,776 to a loss of £42,812 with the most profitable system being HFS. The total profit for all dairy systems was 0.5, 3.1, -2.8, and 1.1p/l, for the HFC, HFS, LFC and LFS respectively.

2.4.3 Sensitivity analysis

2.4.3.1 Feed price volatility in S1 and S2

In S1, applying MP1 and CP2, the effect of reducing concentrate feed costs by 10% caused total variable costs to reduce on average by £62,210 and £8,985 for the LF and HF systems respectively, compared to CP1. The reduction in concentrate costs resulted in a 76% increase in total profit for LFS however the LFC system still suffered a loss of -£992. Applying CP3 in S1, thus increasing the price of concentrate feed by 10%, results in reduced profits of £9,007, £8,622, £61,823 and £61,206, for HFC, HFS, LFC, and LFS respectively. The most profitable system in this case was HFS which generated a total profit of £37,782, while LFC made a substantial loss of £176,936 (Table 2.5)

In S2, the effect of reducing concentrate feed costs by 10% caused total variable costs to reduce for all systems on average by £8,072 and £27,389 for the HF and LF systems respectively. This cost reduction increased the margin per litre by 0.65p for HF systems, and due to a greater reliance on purchased feeds 1.6 p/l for LF systems. The LFS, HFS and HFC returned a profit of 3.8, 2.7 and 1.3 p/l while the LFC system lost

1.1p/l. Similarly in S2, increasing feed costs by 10% caused production costs to increase by 4% and 2% for LF and HF feed systems respectively, and this increase in costs reduced profitability for all systems by a mean of £17,498. Applying CP3 in S2 meant that the only feasible system was HFS with total profits of £32,751 equivalent to 3.26 p/l profit. Losses amongst the other systems were 0.05, 0.4 and 4.4 p/l for the HFC, LFS and LFC systems respectively (Table 2.6).

2.4.3.2 Milk price volatility in S1 and S2

In S1 MP2 CP1, the milk price sensitivity analysis highlighted that reducing milk price resulted in all dairy systems becoming loss making with total losses ranging from £23,552 in the HFS system to £301,999 in the LFC system. These figures represent an average reduction in total profit of £69,047 for the HF systems and £191,756 for the LF systems. The S genotype had approximately 4% less losses than the C genotype. In S1 MP3 CP1, the effect of increasing milk price allowed all systems to generate profits which ranged from £80,645 for HFC to £229,012 for LFS. The LFS followed by the LFC systems were most profitable due to the greater volume of milk produced, the LF FS generated over 100% more total profits than the HF FS (Table 2.5).

In S2, applying MP2 and CP1, the effect of reducing milk price to £0.25, resulted in losses for all systems which ranged from £24,330 for HFS to £120,449 for LFC. Reducing the MP in S2 resulted in total profit reductions of £59,096 to £91,476 for HFC and LFS respectively. The total profit ranged from a loss of 7.0p/l, to a loss of 1.8p/l. In S2, the effect of increasing base milk price to 35p/l resulted in increased total profit for all systems on average by £73,009 ranging from an increase of £59,096 to £91,172 for HFC and LFS respectively (Table 2.6).

Table 2-5 Sensitivity analysis for S1 with a land area of 80 ha under a range of concentrate costs and milk prices.

FS [d]	Concentrate 1 [a]			Concentrate 2 [b]			Concentrate 3 [c]		
	MP1[e]	MP2 [f]	MP3[g]	MP1	MP2	MP3	MP1	MP2	MP3
					Milk Returns £				
HFC	449,850	381,211	518,490	449,850	381,211	518,490	449,850	381,211	518,490
LFC	1,213,671	1,027,773	1,399,568	1,213,671	1,027,773	1,399,568	1,213,671	1,027,773	1,399,568
HFS	466,997	396,523	537,471	466,997	396,523	537,471	466,997	396,523	537,471
LFS	1,312,943	1,115,501	1,510,385	1,312,943	1,115,501	1,510,385	1,312,943	1,115,501	1,510,385
					Feed Costs p/l				
HFC	0.120	0.120	0.120	0.114	0.114	0.114	0.127	0.127	0.127
LFC	0.200	0.200	0.200	0.184	0.184	0.184	0.217	0.217	0.217
HFC	0.114	0.114	0.114	0.108	0.108	0.108	0.120	0.120	0.120
LFS	0.189	0.189	0.189	0.173	0.173	0.173	0.204	0.204	0.204
					Total Costs £				
HFC	492,249	492,751	491,747	483,068	483,570	482,567	501,429	501,931	500,928
LFC	1,447,737	1,449,066	1,446408	1,385,574	1,386,903	1,384,245	1,509,900	1,511,229	1,508,571
HFS	473,213	473,731	472,695	464,422	464,940	463,905	482,003	482,521	481,485
LFS	1,387,554	1,388,977	1,386,132	1,325,297	1,326,720	1,323,875	1,449,811	1,451,233	1,448,388
					Total Profit £				
HFC	12,327	-55,811	80,465	21,334	-46,804	89,472	3,321	-64,817	71,459
LFC	-115,112	-301,999	69,456	-53,995	-239,836	130,574	-176,936	-364,162	8,429
HFS	46,404	-23,552	116,360	55,027	-14,930	124,983	37,782	-32,175	107,738
LFS	32,993	-163,631	229,012	94,198	-101,821	290,218	-28,213	-225,887	167,806
					Profit p/l				
HFC	0.010	-0.040	0.059	0.016	-0.033	0.066	0.003	-0.046	0.053
LFC	-0.031	-0.081	0.019	-0.015	-0.065	0.035	-0.048	-0.098	0.002
HFS	0.034	-0.016	0.083	0.040	-0.010	0.089	0.027	-0.022	0.077
LFS	0.008	-0.041	0.058	0.024	-0.026	0.073	-0.007	-0.057	0.042

[a] Concentrate cost 1: High Forage = £275.00, Low Forage = £302.50. [b] Concentrate cost 2: High Forage = £247.50, Low Forage = £272.50.[c] Concentrate cost 3: High Forage = £302.50, Low Forage = £332.75.

[d] FS = Feed Systems; HFC=High Forage Control, LFC=Low forage Control, HFS=High Forage Select, LFS = Low forage Select. [e] MP1 = 30p/l, [f]MP2 = 25p/l, [g]MP3 = Milk Price 35p/l.

Table 2-6 Sensitivity Analysis for S2 with a fixed herd size under a range of concentrate costs and milk prices.

FS [d]	Concentrate 1 [a]			Concentrate 2 [b]			Concentrate 3 [c]		
	MP1[e]	MP2[f]	MP3[g]	MP1	MP2	MP3	MP1	MP2	MP3
	Milk Returns £								
HFC	388,966	329,435	448,497	388,966	329,435	448,497	388,966	329,435	448,497
LFC	498,326	421,110	575,542	498,326	421,110	575,542	498,326	421,110	575,542
HFS	433,845	368,257	499,433	433,845	368,257	499,433	433,845	368,257	499,433
LFS	604,251	512,418	696,084	604,251	512,418	696,084	604,251	512,418	696,084
	Feed Costs p/l								
HFC	0.120	0.120	0.120	0.113	0.113	0.113	0.126	0.126	0.126
LFC	0.199	0.199	0.199	0.183	0.183	0.183	0.216	0.216	0.216
HFC	0.114	0.114	0.114	0.108	0.108	0.108	0.120	0.120	0.120
LFS	0.188	0.188	0.188	0.172	0.172	0.172	0.203	0.203	0.203
	Total Costs £								
HFC	430,086	430,521	429,651	422,124	422,559	421,689	438,049	438,484	437,614
LFC	590,558	591,110	590,006	564,737	565,289	564,185	616,378	616,930	615,826
HFS	442,048	442,530	441,566	433,867	434,349	433,385	450,229	450,711	449,747
LFS	633,366	634,027	632,704	604,409	605,071	603,747	662,322	662,984	661,661
	Total Profit £								
HFC	6,354	-52,742	65,450	14,165	-44,931	73,262	-1,458	-60,554	57,639
LFC	-42,812	-120,449	33,852	-17,425	-94,629	59,238	-68,501	-146,269	8,466
HFS	40,776	-24,330	105,882	48,801	-16,305	113,906	32,751	-32,354	97,857
LFS	20,957	-70,519	112,129	49,425	-41,747	140,597	-7,511	-99,476	83,661
	Profit p/l								
HFC	0.005	-0.043	0.054	0.012	-0.037	0.062	-0.000	-0.050	0.047
LFC	-0.027	-0.077	0.022	-0.011	-0.060	0.039	-0.044	-0.093	0.005
HFS	0.031	-0.018	0.079	0.037	-0.012	0.087	0.025	-0.024	0.073
LFS	0.011	-0.038	0.060	0.027	-0.022	0.077	-0.004	-0.053	0.044

[a] Concentrate cost 1: High Forage = £275.00, Low Forage = £302.50. [b] Concentrate cost 2: High Forage = £247.50, Low Forage = £272.50. [c] Concentrate cost 3: High Forage = £302.50, Low Forage = £332.75. [d] FS = Feed Systems: HFC=High Forage Control, LFC=Low forage Control, HFS=High Forage Select, LFS = Low forage Select. [e] MP1 = 30p/l, [f]MP2 = 25p/l, [g]MP3 = Milk Price 35p/l.

2.5 Discussion and conclusions

The motivation behind this research was to quantify the influence of genetic merit and management regime on the profitability of contrasting milk production systems and to identify their sensitivity to feed and milk price volatility. Biological herd performance data generated by the Langhill systems experiments and simulated within the MDSM alongside industry average figures, describe the differences in financial performance under two scenarios which applied a range of milk prices and feed costs. The MDSM simulations were based on limiting factors of available land and/or a fixed herd size, which affected total output, costs and ultimately profit.

2.5.1 Comparison of Simulated Outputs

In both scenarios, as milk price and feed price changed within all systems, simulations generated per litre net margins in a range of 9p/l profit to a 9p/l loss and similar findings were outlined by DairyCo (2014), where net margins ranged from a loss of 10p/l to a net profit of 10p/l. Wilson (2011) found net profits and losses of approximately 6p/l depending on the costs associated with production and the level of efficiency at which resources are utilized. Dairy system profitability varies depending on the level of production and the operating efficiency of the system (Wilson, 2011; Kelly et al., 2012). Results generated here were in line with farm revenue figures reported in the UK (DairyCo, 2014; Wilson, 2011), and Table 2.7 shows that the MDSM seems to provide a reliable indication of profitability of diverse genetic merits within housed and composite regimes.

Total fixed costs averaging 9.8 and 6.8 p/l for HF and LF FS's simulated by the scenarios are lower than Milkbench estimates which lie between 11.4 to 18.1p/l for composite and high output systems (Table 2.7). However this variation could stem from large differences in herd size, higher milk yields per cow and thrice daily milking differences. The maximum Milkbench high output herd size was 211 and the maximum yield was 8,959 litres per cow per year (DairyCo, 2012). However it is possible that this study has not fully captured fixed costs associated with confined systems due to assumptions made regarding contractor use, milking and housing facilities and labour requirements.

Simulated feed costs across the scenarios averaged from 10.8 to 21.7p/l which is higher than the 9.8 to 13.1p/l range (Table 2.7) found in the composite and high output farms surveyed for the DairyCo Milkbench study (DairyCo, 2014). However, in the HF FS, the feed costs averaged 11.7p/l and an average feed cost of 19.5p/l for the LF FS system reflects an average concentrate input of 4,060 kg DM whereas the Milkbench average was 2,625 kg DM (DairyCo, 2014). Herd replacement costs generated by S1 and S2 ranged from 4.0 to 6.4p/l at rates of 30% and 32% for Control and Select cows respectively which compare favourably with the Milkbench figure of 4.2p/l in a composite system with a 30% replacement rate. A replacement rate difference of 2% was applied in the MDSM however some studies have shown greater replacement rate differences associated with genetic selection for milk production (Horan et al., 2004; Evans et al., 2006).

The cost of replacing a cow are second only to feed costs, and high replacement rates result in fewer cost reduction opportunities at farm level. Decreasing voluntary culling of all but the least productive animals can extend breeding opportunities (Heikkila et al., 2008) and could increase longevity in a herd especially if carried out in conjunction with importing heifers with more favourable genetic merits. Research suggests that economically beneficial optimal culling policies should not be based solely on potential to produce milk and should also include health characteristics (Stott and Kennedy, 1993). Labour costs simulated in the model averaged 6.2 and 4.3 p/l for HF and LF systems (Table 2.7) and are comparable to a 3.7 to 10.8 scale reported for labour costs within composite and high producing systems (DairyCo, 2014) and also TMR systems (DairyCo, 2010). The simulations results sit at the lower end of the Milkbench range because labour costs have been diluted by larger herd sizes and by the extra volume generated by thrice daily milking. This study could be improved by more detailed information regarding differences in labour requirements between feed systems and genotypes.

2.5.2 Influence of Genetic Merit on Profit

Studies with similar objectives highlight the influence of genetics on farm profitability within various types of grass-based FS’s (Shalloo et al., 2004a; McCarthy et al., 2007; Roche et al., 2006). On average, with equal herd sizes, the S merit produced 11.5%

more milk than the C merit in the composite HF FS and 21.4% more milk than the C merit in the confined LF FS. When comparing systems with an equal land area of 80ha the S merit produced 3.8% more milk on average than the C merit in the composite HF FS and 8.4% more milk on average than the C merit in the confined LF FS. The scenario comparison of diverse Holstein Friesen strains, within traditional UK composite and high output confined dairy FS's presented here, shows the C merit attains an average of 57.8% less profit than the S merit within the HF FS. In the confined LF FS the C merit achieved an average of 78.4% less profit compared to the S merit.

Across all scenarios, when milk price to feed cost ratio is plotted against per litre profitability and linear regression applied, on average, the S merit attains 4p more profit than a C merit when placed in a housed regime and 2p more profit than a C merit when in a composite regime (Figure 2.1) which suggests a scaling effect. Figure 2.1 highlights that irrespective of feeding system, S merits become profitable at a lower milk price to feed cost ratio than the C merit. Confining a herd of average UK genetic merit Holstein Friesian cows and offering a high concentrate diet would only deliver substantial profit at high milk price to feed costs ratios albeit with a large herd size and significant increased cost at farm level.

2.5.3 Influence of Feed System on Profit

Herd profitability is to some extent governed by the combined effect of the genetic potential of the animal, and the feed system adopted by the farmer (Holmes et al., 2002). McCarthy (2007) highlights the inaccuracy of generalizing differences in economic effects derived from diverse genetics across a range of management systems and this can be seen from the variation in profitability achieved by cows of the same merit within the HF and LF feed systems. Scenario results showed a greater difference in profits and losses between the S and C genotypes in the LF FS compared with the HF FS which arises from the cost and levels of purchased feeds. Whilst the LF system has the capacity to achieve greatest profits, particularly at high milk to feed price ratios, the inverse is true at low ratios where the propensity for losses within the LF system can be much higher. Potential yields from cows of lower or higher genetic merits are not sufficient to justify higher feed costs associated with intensive confined systems.

Volume based milk pricing policies, as operated within the UK dairy industry, incentivise systems of production that deliver high output. Encouragements for volume in the liquid milk market largely stem from the ability of processers to reduce transport costs and carbon emissions by attaining a full tanker from the lowest number of farms. Quinlan (2013) suggest that a volume based bonus as operated in the UK can dramatically exaggerate the economies of scale associated with larger volume based collections. The distribution of system profitability estimated by the model can be described as a function of revenues from milk plus livestock sales minus fixed and variable costs. Scenario 1 results showed that whilst absolute revenue attained from the HFS system was much less than the LF FS's, the HFS profits and margin per litre are higher (Table 2.3).

This study assumed that grass growth was 10 t DM/Ha and no effect of grass growth was included in the simulation even though it is appreciated that a wide variation in silage and grazing yields exists. A key feature of increasing output in the future will centre on expanding forage production and the cost of forages in both FS's discussed here could be reduced by improving growth and utilization of grass. Improved yields by increasing t DM/Ha in conjunction with increased forage quality will reduce costs as well as the requirement for land. Improving pasture management, for example by utilizing grass measurement techniques could increase production from forage (O'Donovan et al., 2002).

At farm level, moving from a profitable genetically select herd in a HF grazing system to a LF management regime will result in greater exposure to both input and output price volatility albeit with a propensity to generate large profits at high milk price to feed costs ratios (Fig. 1). Even though total attainable profit could be greater in LF FS's, scenarios applied in this study show the HFS FS was always more profitable on a per litre basis and not as exposed to milk and concentrate price volatility. When a milk to feed price ratio is applied as in Figure 2.1, the effect of difference in FS concentrate price within the model is apparent because when milk price is high and feed cost low the LFS system achieves equivalent profitability at a slightly lower ratio than in the HFS system.

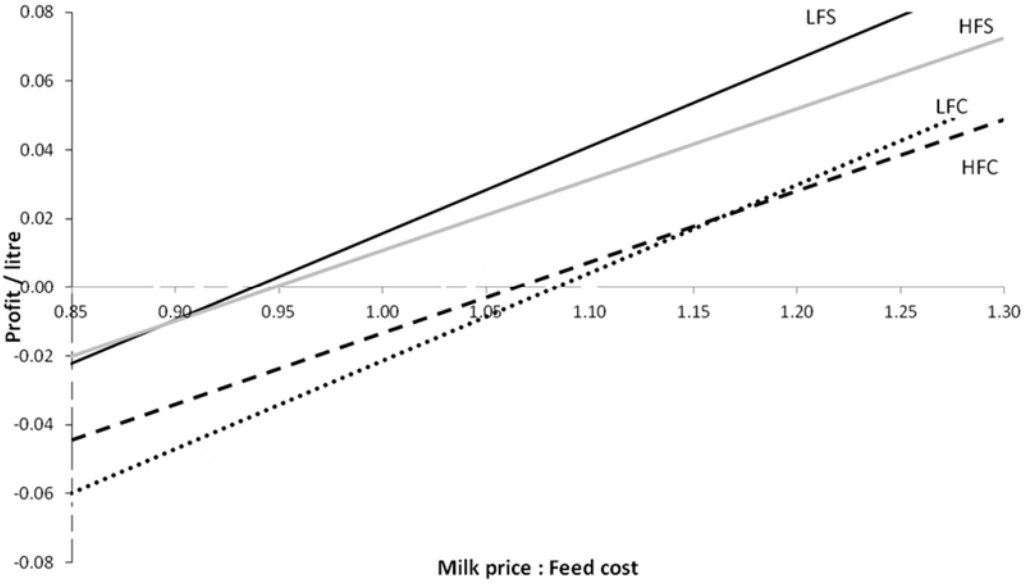


Figure 2.1 Line graph showing production system [a] per litre profitability at a range of milk price to feed cost ratios

[a] HFC=High Forage Control, HFS=High Forage Select, LFC=Low Forage Control, LFS=Low Forage Select

As with most modelling tasks, limitations are inherent within the process and can cause aspects of the model to appear imperfect. Examples of weakness in this financial simulation could be the assumption that herbage (grazed grass and silage) production and utilisation were the same for both systems and also that contractors would carry out feeding operations. These assumptions could have led to underestimated fixed costs. Breeding objectives also vary as different countries can adopt diverse goals, and whilst the FS's described here would not be applicable to smallholder farmers the regimes are not dissimilar to those practised across the world including the EU, New Zealand and North America.

2.6 Conclusions

The simulation model applied here allows a financial comparison of contrasting UK dairy systems selling liquid milk and generates results consistent with similar benchmarked analysis. Model outputs highlight the economic consequences of biological change under controlled management and evaluate financial performance under a combination of scenarios. Observed differences can be attributed to genetics, feed system or a combination of both. Results illustrate that genetic selection for increased production leads to substantial improvement in financial performance compared to an average UK merit when there is little deterioration in herd fertility, because increasing cow longevity or reducing replacement rate decreases production costs regardless of feed costs. Scenarios show that higher yields are not a solution if they are derived at the expense of feed costs. Systems operating on low cost inputs will be more financially sustainable under fluctuating milk and feed prices. Results emphasise the importance of dairy system selection at farm level and allude to the susceptibility of regimes interested in high volume production that is often encouraged by processors. In order to endure a volatile price environment, farmers operating continuously housed systems could retain a proportion of profits at high price ratios or modify their system in periods of low ratios. This research does not represent a complete range of dairy regimes found in the UK and the results presented here raise a question as to whether greater profitability could be achieved by high producing cows in dairy systems with lower concentrate inputs that focus on grazing, albeit with lower yields. Whilst this was outside the remit of this work, the model will allow follow on studies looking at increased forage-based systems. Further research could also be carried out to assess the financial outcomes of reduced replacement rates across the systems and this is explored in the next chapter which examines health attributes amongst the dairy systems.

Chapter Three

3 Financial and production effects of herd health parameters in housed and composite dairy production systems.

3.1 Summary

Optimising heifer rearing and minimising herd replacement rates are key features of dairy production where farmers can implement strategies to control costs in order to maximise profitability. Reducing herd replacement rate has the combined effect of increasing milk output as well as lowering replacement costs at farm level. Irrespective of system type, increasing age at first calving (AFC) beyond 24 months alters the age profile of the herd, leading to increased feed and replacement costs. The objective of this chapter was to determine economic effects of modelled herd fertility improvements and differences in AFC. Physical and financial performance results are presented at varied replacement rates and first calving ages to describe the consequences of different heifer rearing and culling strategies in the herd on overall farm profitability. Reducing replacement rate by 1% in a herd of improved merit Holstein Friesian cows could increase profits by up to 0.3p/l in a housed system and by 0.4p/l in a composite system. In a 200 cow herd of improved genetic merit animals, the effect of reducing replacement rate by 1% per year could effectively increase profits per cow by £30 in a confined system with a high concentrate diet and £34 in a composite system, with cows consuming a High Forage diet. Increasing age at first calving, from 24 to 35 months in a herd of improved merit Holstein Friesian cows could decrease annual profits by up to 0.21 ppl monthly in a confined system, housing cows all year round and 0.24 ppl monthly in a composite system, housing for part of the year. In a 200 cow herd of improved genetic merit animals, the effect of calving one month later from 24 months onwards could effectively decrease annual profits per cow by £19.05 in a confined system with a Low Forage diet, housing all year round and £14.72 in a composite system, for a High Forage diet housing part of the year.

3.2 Introduction

Ongoing financial challenges facing the UK dairy industry could be described as a function of global market volatility generated by slumps in demand combined with rising milk production as well as a loss of competitiveness within the sector. Whilst milk price and the cost of imported feeds are largely beyond the control of individual enterprises, the expense of maintaining a herd is principally governed by the farm manager, based mainly on the system operated and the levels of technical competence of the system operated. Replacement costs are generally second only to feed and forage outlays (Wilson, 2011; DairyCo, 2014).

Generally, there is no annual payment for herd depreciation, the costs associated with rearing or purchasing replacement heifers with the income received from culled cows only marginally offsetting the heifer costs (DairyCo, 2012). An annual herd replacement rate can be evaluated by calculating the proportion of cows leaving a herd due to culls, sales or deaths. Estimates for the UK indicate a median culling rate of 24%, with an inter quartile range of +/-10% (Hanks and Kossaibati, 2014), while costs of replacements have been shown to average 3.2p/l (DairyCo, 2012). A wide interquartile range suggests that the expense could be reduced by targeting preventable causes of animals leaving a herd before the end of their productive life such as infertility, lameness, and mastitis.

The importance of fertility has been found to be significant in pasture-based systems that implement seasonal calving regimes, (Dillon et al., 2006). Improving fertility in pasture-based spring calving systems in Ireland was shown to lower replacement costs by 2.8p/l when replacement rate is reduced by 10% (Shalloo et al., 2014). Irrespective of system type, milk production over multiple lactations is reliant upon pregnancy and reduction in conception rate incurs costs stemming from further artificial insemination (AI), additional labour, extended calving intervals and ultimately increased culling (Shalloo et al., 2014; Esslemont, 2001; Boichard, 1990).

Historic declines in dairy cow fertility resulting from selection for milk production (Pryce et al., 1999) are reported to be reversing in some countries due to recognition of the importance of fertility traits within breeding programs (Pryce et al., 2014). Nevertheless, management and environment can also affect reproductive performance

(Walsh et al., 2011, LeBlanc, 2010). In the UK, an increased ability of heat detection at first service has been found to assist in preventing decline however, infertility continues to be described as one of the main reasons for culling dairy cows (DairyCo, 2012).

Key performance indicators (KPI's) are analytical tools which provide an understanding of the utilisation of resources or efficiency of individual farms. KPI's can be used to benchmark farm performance by comparing with farms utilising similar production methods to improve productivity and/or financial performance. Age at first calving is a KPI attributed to dairy management systems as calving patterns determine both the milk supply profile and feed requirements for cows throughout the year. AFC is also an area of the production system directly under the control of the farm manager.

Financial goals associated with rearing replacement heifers can be described as minimisation of inputs whilst ensuring maximum profitable outputs (Hoffman and Funk, 1992). Reduction of inputs can be achieved by appropriate heifer nutrition and management to optimise rates of growth to achieve a lower AFC (Heinrichs et al., 2017). In the US Holstein AFC averaged 28 months in 1980, 25.5 months in 2004 (Hare et al., 2006) with some figures also showing an average AFC of between 23-24.5 months for Holsteins (Pirlo et al., 2000; Ettema and Santos, 2004; Heinrichs et al., 2013). Decreases in AFC will eventually cease as calving too early can be associated with reduced milk yield and increased incidence of dystocia and can affect the size of new-born calves (Hoffman and Funk, 1992, Kamal et al., 2014). Delaying AFC in Holstein Friesian cows from 24 months to 36 months has been shown to increase body weight by 10% and decrease lifetime milk yield by up to approximately 3,500 kg (Dewhurst et al., 2002; Hutchison et al., 2017).

This analysis quantifies economic and production effects of lowering herd replacement rates and optimising AFC within high output and composite dairy systems across two genotypes of Holstein Friesian cows using the Moorepark Dairy Systems Model (MDSM) (Shalloo et al., 2004) which has been extensively applied to evaluate effects of farm level economic and technical changes in spring calving and all year round production systems (Shalloo et al., 2004a; March et al., 2017).

3.3 Methods

3.3.1 Dairy systems description

Herd production data from a 5-year long experiment at SRUC’s Crichton Royal Farm, Scotland was used to model the financial performance of each management system. The dairy systems experiments are part a long-term study to assess the effect of genetic line × feeding regime interactions as described by Pollott and Coffey (2008). Some recent examples of the use of Langhill data to illustrate environmental and health effects of dairy systems include (Ross et al., 2014; Randall et al., 2015; March et al., 2016).

Comprised of two divergent genetic lines, one selected for production of milk fat plus crude protein (CP) yield, the Select line (S) represents the top 5% of UK genetics and the Control line (C) denote UK average genetics. Milking cows were allocated to either: a low forage (LF) diet within a housed system; or a high forage (HF) diet in a grazing system where cows were housed when grass growth was insufficient. Diets were fed as a total mixed ration (TMR) and concentrate in the milking parlour. Table 2.2 in Chapter 2 shows concentrate and forage dietary inputs, milk production, milk composition, body weight, and reproductive performance data averaged over 5 years between 2006 and 2010.

3.3.2 Moorepark Dairy Systems Model (MDSM)

In the past the MDSM has been used to evaluate the effect of different components of grazing systems based in Ireland (Shalloo et al., 2004; Ryan et al., 2011) and composite and housed UK dairy systems (March et al., 2017). The MDSM combines animal inventory and valuation, milk production, feed use, land and labour needs, with an economic analysis. Variable costs such as fertilizer, contractor charges, veterinarian fees, artificial insemination, silage, and fixed costs including machinery, farm maintenance, telephone, electricity, and expenses (calf, milk, and cow) were based on values described Chapter 2. Purchased concentrate feed was priced at £275/T fresh weight (FW) for the HF system. The LF concentrate feed was 10% more expensive at a FW cost of £302.50/T, to account for a higher spec concentrate fed in this system. Land not utilized by the dairy system was leased out at £272 per hectare and all systems and all systems obtained a base milk price of 30p/l (MP1).

3.3.3 Parameters for economic comparison

Replacement rate scenarios were carried out on a simulated dairy holding with land area totalling 80ha, and farming with a fixed herd size of 200 cows. One subsequent scenario within the confined LFS system with a larger herd size of 430 cows was applied to investigate the effect of replacement rate differences and this was carried out by maximising ‘on farm’ land use. Milk contract prices were based on a typical UK liquid purchasing agreement which comprised of a base price plus bonuses and penalties implemented when milk or hygienic quality differed from a prescribed range. A volume bonus stemming from production added a minimum of 0.2 p/l and a maximum of 3.2 p/l.

3.3.4 Replacement rates

For high-producing HF cows a reduction in calving interval can have a positive effect on average daily yields as animals spend less time in late lactation and not lactating. Improved herd fertility was modelled through reducing calving interval from 430 to 400 and 370 days respectively and herd parity structure changes to emulate a greater proportion of mature cows at a replacement rate range from 22% to 32%. Heifers have been shown to produce 20% less milk per day on average than animals in later lactations (Coffey et al., 2002). Select cow replacement rates of 24%, 28% and 32% and control cow rates of 22%, 26% and 30% are applied. Following discussion with stakeholders a 2% difference was applied to S and C genotypes to represent variation in culling rates found during the trials.

Simulations represent a feasible range of replacement rates found within composite and high output systems on UK dairy farms (DairyCo, 2014, Hanks and Kossaibati, 2013). Calving patterns for the C and S genotypes were calculated as the proportion of cows within each genotype and parity that calved in each month throughout the year. This was adjusted by parity structure, with an equal number of cows calving in each month to simulate an all-year-round calving pattern.

3.3.5 Sensitivity analysis – Effect of milk price variation

Analysis was carried out to examine financial implications of milk price variability under a range of replacement rate scenarios. Milk prices included in the sensitivity analysis were 25 p/l and 35p/l to represent a low (MP2), and high (MP3) milk prices, respectively. A milk price range of 25p/l to 35p/l is similar to variations seen in the UK since 2010 (Defra, 2017).

Table 3-1 UK costs associated with dairy enterprises and applied with the MDSM

Item	Amount
Silage value per tonne of DM	£130[a]
Maize value per tonne of DM	£150[a]
Alkalage value per tonne of DM	£140[a]
Opportunity cost of land / Ha	£200[b]
Vet call out + drugs cost	£45[b]
A.I. price per straw	£30.50[b]
A.I. price per service	£11.40[b]
TB call out	£60.00[b]
TB test cost per cow	£1.60[b]
Average price of agricultural diesel per litre	£0.53[c]
Machinery hire slurry 41m^3 / hour	£50[d]
Diet feeder hire per hour	£30[d]
Silage contractor costs per ha	£160[b]
Average electricity standing charge	£15[b]
Average electricity cost pence per unit	£0.13[b]
Average housing cost per cow	£2,500[b]
Average cost per cow for a milking plant	£5,000[b]
Fertiliser urea £ / T 46 % N	£185[a]
Fertiliser ammonium nitrate £ / T 27.5 % N	£145[a]
Managers salary per hour	£15[c]
General operative salary per hour	£10[c]

DM = Dry Matter, A.I. = Artificial Insemination, TB = Tuberculosis
[a] SAC (2017), [b] AHDB expert advice, [c] UK Government (2013), [d] National Association of Agricultural Contractors (NAAC), [e]

3.3.6 AFC Scenarios

Scenarios aimed to demonstrate differences in financial outcomes resulting from good, average and poor AFC performance at 24, 27, and 30 months of age, respectively. Resulting replacement rates modelled in the AFC scenarios from 2 years to 3 years ranged from 30% to 42%, with S herds attracting rates between 32% and 42% and C cows between 30% and 40%. A 2% replacement difference between the S and C genotypes was applied to represent actual differences found between the herds during experimental conditions. Model parameters were reviewed, and a selection of cost parameters were updated as more recent data became available and these are outlined in Table 3.1.

Table 3-2 Effect of herd replacement rate on key production parameters and profitability for S and C merit within a confined dairy management system

	LFS			LFC		
Herd replacement rate	32%	28%	24%	30%	26%	22%
Farm Size (ha)	80	80	80	80	80	80
Total ha used	37	38	39	33	34	35
Number of cows calving	200	200	200	200	200	200
Average milk yield kg per cow	10,553	10,853	11,153	8,824	9,124	9,424
Butter fat %	3.87	3.86	3.86	3.62	3.61	3.61
Protein %	3.31	3.31	3.31	3.08	3.08	3.08
MS / kg cow	757	778	799	591	611	630
Average BW kg / cow	625	625	625	614	614	614
Total grazed grass / cow	0	0	0	0	0	0
Total kg DM silage per cow	2353	2383	2414	2085	2112	2139
Total kg DM maize per cow	709	719	730	623	632	642
Total kg DM alkalage per cow	472	479	486	415	422	428
Total kg DM concentrate per cow	4309	4369	4430	3812	3865	3920
Total Kg DM intake per cow	7843	7950	8060	6936	7031	7129
Labour hours per cow / year	32	33	33	32	33	33
Milk produced kg	1859949	1946188	2034261	1567598	1649511	1732585
Milk sales kg	1836669	1922908	2010981	1544318	1626231	1709305
Fat sales kg	71004	74238	77538	55864	58743	61660
Protein sales kg	60714	63579	66505	47566	50097	52665
Livestock sales £	51091	48770	46414	49551	47231	44932
Replacement costs £	82972	72762	62411	77994	67550	57212
Labour costs £	92196	93241	94281	92667	93733	94768
Total fixed costs	139791	141290	142790	139703	141092	142430
Total variable costs	459983	461071	462278	417241	416993	416966
Milk Price 30p/l						
Milk returns £	604251	633427	662288	498326	522202	549140
Margin/cow £	-17	103	222	-337	-235	-120
Margin/kg milk £	0.00	0.01	0.02	-0.04	-0.03	-0.01
Total profit £	-3409	20692	44328	-67347	-47094	-24065
Milk Price 27p/l						
Milk returns £	549151	575740	601959	451996	473415	497861
Margin/cow £	-291	-183	-78	-570	-480	-376
Margin/kg milk £	-0.03	-0.02	-0.01	-0.07	-0.06	-0.04
Total profit £	-58112	-36579	-15566	-114008	-96050	-75215
Milk Price 24p/l						
Milk returns £	494051	518052	541629	405667	424629	446582
Margin/cow £	-568	-472	-379	-803	-726	-634
Margin/kg milk £	-0.06	-0.05	-0.04	-0.10	-0.09	-0.07
Total profit £	-113605	-94384	-75745	-160668	-145186	-126861

[1]LFS=Low forage select [2]LFC=Low forage control

Table 3-3 Effect of herd replacement rate on key production parameters and profitability for S and C merit within a grazed dairy management system

	HFS			HFC		
Herd replacement rate	32%	28%	24%	30%	26%	22%
Farm Size (Ha)	80	80	80	80	80	80
Total Ha used	74	78	81	69	73	76
Number of cows calving	200	200	200	200	200	200
Average milk yield kg per cow	7,575	7,875	8,175	6,833	7,133	7,433
Butter fat %	4.01	4.00	4.00	3.81	3.80	3.80
Protein %	3.29	3.29	3.29	3.15	3.15	3.15
MS / kg cow	553	574	596	475	496	516
Average BW kg / cow	608	608	608	580	580	580
Total grazed grass / cow	1815	1892	1968	1650	1724	1798
Total kg DM silage per cow	2311	2338	2365	2173	2198	2224
Total kg DM maize per cow	723	733	742	678	687	696
Total kg DM alkalage per cow	723	733	742	678	687	696
Total kg DM concentrate / cow	1334	1349	1365	1288	1303	1317
Total Kg DM intake per cow	6906	7044	7183	6466	6598	6731
Labour hours per cow / year	34	34	35	34	35	35
Milk produced kg	1335034	1412165	1491086	1213907	1289562	1366543
Milk sales kg	1311754	1388885	1467806	1190627	1266282	1343263
Fat sales kg	52585	55596	58673	45326	48132	50984
Protein sales kg	43159	45707	48314	37451	39837	42265
Livestock sales £	50545	48291	46004	48527	46343	44180
Replacement costs £	82972	72762	62411	77994	67550	57212
Labour costs £	80412	81293	82170	80798	81696	82569
Total fixed costs	126197	127500	128805	126236	127554	128848
Total variable costs	267187	262671	258108	254902	249926	245085
Milk Price 30 p/l						
Milk returns £	433845	459930	486433	388966	413998	437826
Margin / cow £	158	293	429	-14	118	243
Margin / kg milk £	0.02	0.04	0.06	0.00	0.02	0.04
Total profit £	31666	58522	85805	-2757	23566	48605
Milk Price 27 p/l						
Milk returns £	394492	418263	442399	353247	376009	397528
Margin / cow £	-37	86	210	-191	-71	43
Margin / kg milk £	-0.01	0.01	0.03	-0.03	-0.01	0.01
Total profit £	-7398	17162	42095	-38214	-14145	8601
Milk Price 24 p/l						
Milk returns £	355140	376597	398365	317528	338021	357230
Margin / cow £	-232	-121	-8	-368	-259	-157
Margin / kg milk £	-0.03	-0.02	0.00	-0.06	-0.04	-0.02
Total profit £	-46461	-24198	-1616	-73672	-51856	-31402

[1]HFS=High forage select [2]HFC=High forage control

3.4 Results

Key herd parameters and profitability indices at each of the replacement rate scenarios ranging from 22% to 32% and milk prices of 24 p/l, 27 p/l and 30 p/l are presented in Table 3.3 and Table 3.4 for LF cows and HF cows of both genetic lines, respectively.

3.4.1 Low Forage Select Genotype

At a milk price of 30 ppl, with a herd of 200 confined improved merit cows, consuming a low forage diet, with a replacement rate of 32% would result in an estimated annual loss of £17 per cow, even though each animal is yielding an average of 10,553 kg of milk. As calving interval falls and replacement rate is decreased to 28% and 24%, average milk yields increased to 10,853 kg and 11,153 kg respectively which corresponded to an additional annual income from milk sales of £29,176 and £58,037 compared to a 32% rate. Total dry matter feed intakes increased from 7.84 tonnes to 7.95 and 8.06 tonnes per cow as replacements decreased and an average of 1.15 extra hectares of land were required per 4% decrease in replacement (Table 3.3).

At 32% replacement, a base milk price of 30 ppl was not enough to prevent annual losses, however a 4% and 8% rate improvement resulted in profits of £20,692 or £103 per cow and £44,328 or £222 per cow, respectively. Costs of replacements at 32%, 28% and 24% were 45 ppl, 37 ppl, and 31 ppl, respectively. For each 1% decrease in replacement rate achieved, an increase in profitability of £0.003 per litre or £30 per cow was indicated, a breakeven replacement rate of 31.4% (Figure 3.1). As the replacement rate decreased from 32%, livestock costs as a percentage of total income decrease from 12.7% to 8.8%. In this scenario feed costs averaged 54% of total production costs at 19 ppl.

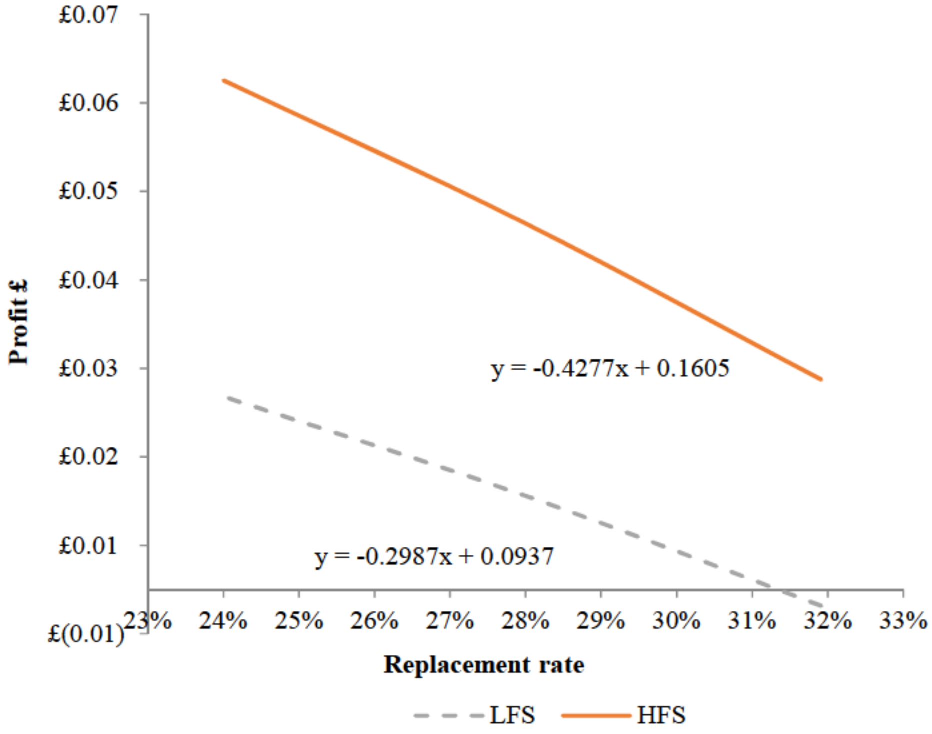


Figure 3.1 Effect of replacement rate on pence per litre profitability across Select genotypes within Low (LFS) and High (HFS) Forage feeding systems

3.4.2 Low Forage Control Genotype

At a 30ppl milk price, average merit cows consuming a low forage diet, with a replacement rate of 30% and producing milk yields of 8,824 kg resulted in an estimated annual loss of £337 per cow. As calving interval decreases and replacement rates improve to 26% and 22%, average milk yields increased to 9,124 kg and 9,424 kg which corresponds to additional income from milk sales of £23,876 and £50,814 respectively, compared to a 30% rate. However, this does not compensate overall and annual losses per cow of £235 and £120 were anticipated. Total concentrate feed intakes averaged 3.8 tonnes per cow and on average 34.3 hectares were required to support 200 cows managed in this system.

Total estimated annual losses stemming from an LFC management regime with a base milk income of 30 ppl ranged from £24,065 at 22% replacement to £67,347 at 30% replacement. Costs of replacement at 30%, 26% and 22% were 50 ppl, 41 ppl, and 33 ppl, respectively, and each 1% decrease in replacement rate corresponded to an increase in profitability of £0.004 per litre or £27 per cow. Results showed a minimum replacement rate of 17.5% would be required to be achieved for the LFC system to break even at a £0.30 base price for milk income (Figure 3.2). As the replacement rate decreased from 30%, livestock costs as a percentage of total income decreased from 14.2% to 9.6%. Costs of feed averaged 52% of total production costs at 20 ppl, and this dairy system was estimated to be unprofitable without a reduction in feed expenses and replacement rates.

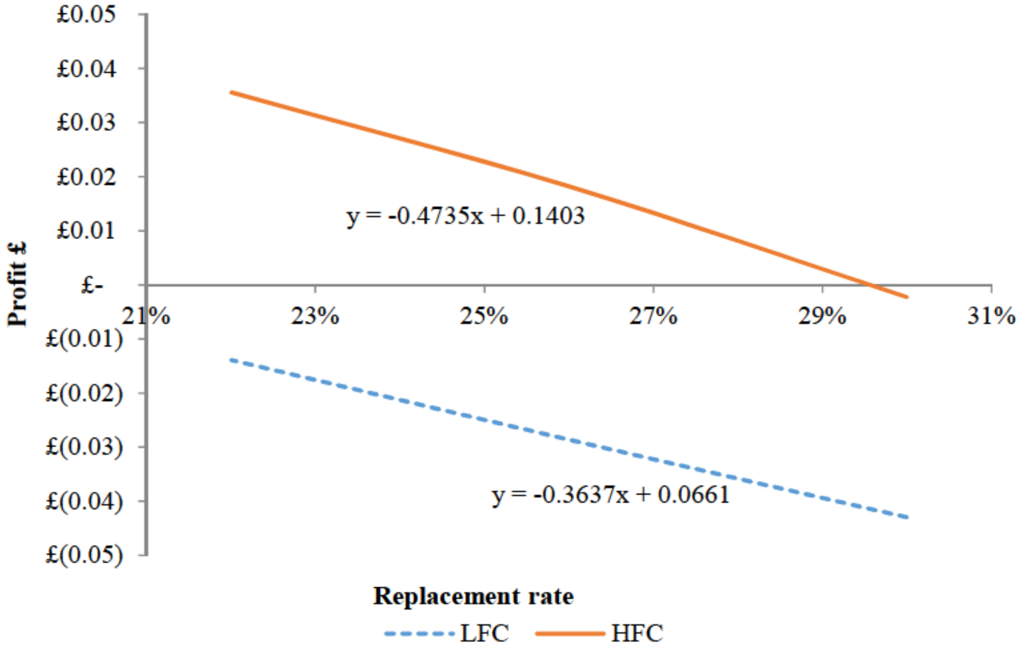


Figure 3.2 Effect of replacement rate on pence per litre profitability across Control genotypes within Low and High Forage feeding systems

3.4.3 High Forage Select Genotype

With a base milk price of 30 ppl, an improved genetic merit herd consuming a high forage diet, at a replacement rate of 32% would produce yields averaging 7,575 kg and estimated annual profits of £31,666, or £158 per cow. As the replacement rate decreased to 28% and 24%, improved fertility and increased milk yields were associated with additional annual profits of £26,857 and £54,140 respectively, taking total profits to £58,522 and £85,805 or £293 and £429 per cow (Table 3.4). Total dry matter feed intakes per animal averaged 7.0 tonnes per cow and land requirement averaged 78 ha across all replacement rates (Table 3.4).

Within this system, costs of replacements ranged from 4.2 to 6.2 ppl as rates increased from 24% to 32% and each 1% decrease in replacement rate resulted in an increase in profitability of £0.0043 per litre or £34 per cow (Figure 3.1). As replacement rate improved from 32%, livestock costs as a percentage of total income decreases from 17.1% to 11.7%. Feed costs within this system averaged 34% of total production costs at £0.11 per litre and were proportionally the lowest when comparing the four management types.

3.4.4 High Forage Control Genotype

A UK average merit herd of Holstein Friesian cows consuming a high forage diet, at a replacement rate of 30%, with a base milk price of £0.30, would lose an estimated £2,757 or £14 per cow. As the replacement rate decreased, improved fertility and milk yield reverse losses and annual profits of £23,566 or £118 per cow at 26%, and £48,605, or £243 per cow at 22% were attained. Total dry matter feed intakes per animal averaged 6,598 kg and land requirement was 73ha on average across all replacement rates (Table 3.4).

Costs of replacement averaged £67,585 and ranged from 4.2 to 6.4 ppl as replacement rates decreased from 30% to 22%. With each 1% decrease in replacement rate an increase in profitability of £0.0047 per litre was projected (Figure 3.2), which equates to £32 per cow. Feed costs in the HFC system averaged 34% of total production costs and £0.12 per litre. As the replacement rate lowered from 30%, livestock costs as a percentage of total income decreased from 17.8% to 11.9%.

3.4.5 AFC Scenarios

With a milk price of 30 ppl, a herd of 200 improved merit cows consuming a LF diet with a replacement rate of 32%, and an AFC of 24 months, would result in an annual profit of £235 per cow, with each animal yielding an average of 10,553 litres of milk. Should AFC increase to 30 months, replacement rate would increase to 36% as cows are more likely to be culled, average milk yields increased to 11,053 kg respectively which corresponded to an additional annual income from milk sales of £58,037, however annual profit per cow fell to £120 per cow in the LFS system.

Table 3-4 The effect of AFC on profit per cow for Select and Control merit within Low and High Forage feeding systems at 30p / litre

	Profit £/cow			
AFC Months	HFS	LFS	HFC	LFC
24	337	235	119	-100
25	322	215	106	-114
26	308	196	93	-129
27	293	177	80	-144
28	278	158	67	-158
29	263	139	54	-173
30	249	120	41	-188
31	234	101	28	-203
32	219	82	14	-217
33	205	63	1	-232
34	190	44	-12	-247
35	175	25	-25	-261

3.5 Discussion

The motivation for this investigation was to quantify the financial influence of optimising AFC and lowering replacement rates across diverse genetic lines of Holstein Friesian dairy cows managed within two contrasting feeding systems. Biological herd performance data generated from Langhill systems experiments and simulated within the MDSM alongside industry average figures illustrate financial performance differences under an equal herd size scenario. Irrespective of system type, reducing replacement rate and AFC alters the age profile of a herd, leading to increased milk production and reduced replacement costs.

Financial benefits of lowering herd replacement rate outweigh an increase in labour costs and feed costs initiated by greater milk production from an older herd. In addition to increased replacement costs, poor fertility in dairy herds attracts costs related to loss of milk production income due to a reduction in the numbers of animals calving, reduced income from calf sales and a lost genetic potential for the and transmission of traits for the animal culled and the next generation. The importance of fertility has been found to be significant in both pasture-based systems with seasonal calving regimes, and confined systems with high yielding cows (Veerkamp et al., 2002; Dillon et al., 2006; Cabrera 2014). Improving fertility in pasture-based systems in Ireland was shown to increase farm profit by 2.2p/l when replacement rate reduced from 28% to 18% in a 100-cow herd (Shalloo et al., 2014).

3.5.1 Effect of production system and genotype

The financial effect of feeding regime is evident in Figure 3.1 and Figure 3.2 as the High Forage system is more profitable on a per litre basis than the Low Forage system, for both Select and Control cows. This is as a result of much lower variable costs in the High Forage system. Within the confined Low Forage system, high quantities of imported feeds, averaging 4.1 tonnes per cow, have led to unmanageable costs which have outweighed income from milk returns. Figure 3.3 provides a comparison of profitability per cow within both feeding systems and genotypes and shows that the HFS system is on average £189 and £240 more profitable per cow than the LFS and HFC, respectively.

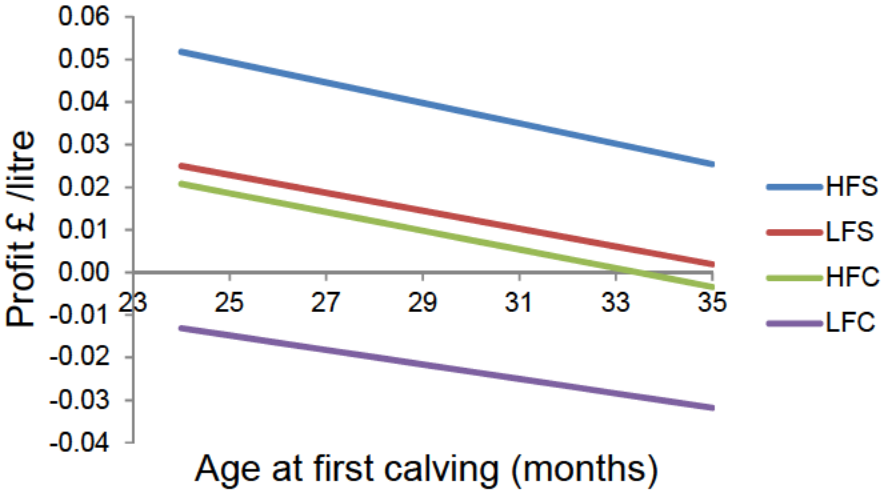


Figure 3.3 The effect of AFC on per litre profit for Select and Control merit within Low and High Forage feeding systems at 30p/ litre

With equal herd sizes, across both feeding regimes cows of a Select genetic merit were heavier, consumed more feed, and produced more milk from a larger land requirement than cows of an average UK genotype. Across all replacement rates, average milk produced and total DM feed intakes from the S merit were 18% and 13% greater in the LF system and 10% and 7% greater in the HF system than the C merit, respectively. The financial effect of genetic strain of animal is illustrated in Figure 3.3 which clearly shows that on a per cow basis the Select genotype is £386 and £245 more profitable than the average genotype in the Low and High Forage management types, respectively. A caveat that must be placed in this analysis is the difference in replacement rate between the select and control cows assumed, which was 2%. If in reality, this was greater than 2% then subsequently the difference in profitability would be less and may even reverse.

3.5.2 Increased herd size within Low Forage system

High output dairy systems such as the Low Forage regime can potentially facilitate larger herds than grazing based dairy management because targeted nutrition can be supplied to confined cows in a more straightforward manner with the vast majority of the feed required purchased into the system. Nutrients within high specification concentrates can be more consistent than grass quality which varies with season and local weather.

The effect of decreased replacement rate with an increased herd size was explored to assess the differences in profitability and also the potential to dilute fixed costs with additional cows. It is anticipated that the effect of expanding herd size from 200 to 430 cows to maximise available land area of 80ha within a LFS system would suggest, on average, across all replacement rates, an increase in profit of £92 per cow or 0.01 ppl Replacement costs as a proportion of income are on average 0.1% less with an increased herd size in the LFS system.

3.5.3 Effect of Milk Price

With a 200-cow herd and a milk price of 24ppl both feed systems and genotypes were unprofitable at all replacement rates. At a milk price of 27 ppl both genotypes within the LF regime were unprofitable at all replacement rates. However, the HFS system attained profits of £0.01 ppl and £0.03 ppl at replacement rates of 24% and 28% respectively. For the HFC system, a 27ppl milk price achieved profits of £0.01ppl at a 22% replacement rate however this system lost £0.03ppl at a 30% replacement rate.

Farm profit was increased by an average of 3.1p/l across the four systems with a range of 2.4p/l to 3.8p/l. Increasing the longevity of dairy cows, and thereby the age profile of the herd can also lead to environmental benefits. Garnsworthy (2004) modelled changes in fertility with links to herd structure, yield, replacements and gas emissions, showing that the main effect of fertility on emissions of methane and ammonia was the number of replacements required to maintain a herd. Bell et al (2011) modelled the effect of improving fertility and longevity using data from the same Langhill systems experiment and showed a slight decrease in GHG emissions per kg of energy corrected milk (ECM) when calving interval was reduced.

3.6 Conclusions

Farm managers have an opportunity to reduce variable costs by monitoring and minimising the expense associated with herd replacements. Controlling costs and making management modifications which improve herd replacement rates by optimising culling decisions could increase profits by £0.003 / litre in a confined system and £0.0043 / litre in composite systems per 1% change in herd replacement rates. With a herd of 200 Holstein Friesian dairy cows of improved merit, reducing replacements by 2 cows /year can effectively increase profits per cow by £30 in a confined system and £34 in a composite system. Reducing replacement rates by 1% or 2 cows in an average genetic merit herd can increase profits by £27 per cow or £0.0036 / litre in a confined herd and £32 per cow or £0.0047 / litre in a composite system. As herd size and volumes of milk sales increased, the effect of a decreased culling rate per litre of milk produced was greater. Irrespective of system type, increasing AFC beyond 24 months alters the age profile of the herd and could decrease annual profits by up to £0.0021 / litre in a confined system, and £0.0024 / litre in a composite system.

Chapter 4

4 Modelling phosphorus efficiency within diverse dairy systems – pollutant and non-renewable resource?

March, M. D., Toma, L., Stott, A. W., & Roberts, D. J., 2016. Modelling phosphorus efficiency within diverse dairy farming systems - Pollutant and non-renewable resource? Ecological Indicators, 69, 667–676.

4.1 Summary

Increased demand for protein rich nutrition and a limited land capacity combine to create a food supply issue which imposes greater dependence on phosphorus, required for yield maximization in crops for humans, and for animal feeds. To determine the technical and environmental efficiency of diverse milk production systems, this work evaluates the use of phosphorus (P), within confined, conventional grazing, and innovative dairy management regimes across two genetic merits of Holstein Friesian cows, by calculating annual farm gate P budgets and applying a series of common and novel data envelopment analysis (DEA) models. Efficiency results provide an insight into P effective dairy management systems as the DEA models consider P as an environmental pollutant as well as a non-renewable resource. We observe that dairy system efficiency differs, and can depend upon, model emphasis, whether it is the potential for losses to the environment, or the finite nature of P. DEA scores generated by pollutant focused models were wider ranging and, on average, higher for genetically improved animals within housed systems, consuming imported by-product feeds and exporting all manure. However, DEA models which considered P as a non-renewable resource presented a tighter range of efficiency scores across all management regimes and did not always favour cows of improved genetics. Divergent results arising from type of model applied generate questions concerning the importance of model emphasis and offer insight into the sustainability of P use within varied dairy systems.

4.2 Introduction

Increasing demand for food and a limited land capacity combine to create a food supply issue, which imposes increased dependence on phosphorus required for yield maximization in crops for humans and for animal feeds. Intergenerational equity regarding the consumption of finite phosphorous reserves demands efficient use of this naturally occurring element, an essential plant and animal nutrient as well as an environmental pollutant. Phosphorus (P) is a key constituent of fertilisers with over 90% of the current 220 million tons of rock phosphate mined annually being used for agricultural purposes (Jasinski, 2014). Even though estimated global P reserves have increased from 50-100 years (Steen, 1998; Smit et al., 2009) to 370 years at present extraction rates (USGS, 2011), concerns relating to resource shortages and security of supply remain. In 2014 the European Commission (EC) added phosphate rock to its critical raw materials list (EC, 2014) and because production of P is controlled by a limited number of countries this can generate geopolitical anxiety (Cordell, 2010).

The UK is akin to most European Union (EU) member states, food security is dependent on imported P fertilisers to sustain crop yields (Cooper & Carliell-Marquet, 2013), and because there is no substitute for this non-renewable resource in agriculture, food security could be improved by moving towards closed loop farming systems. This would increase resource use efficiency, reducing losses to the environment and lowering total P consumption (Childers et al., 2011; Cooper & Carliell-Marquet, 2013).

In dairy systems, P can be imported onto the farm within animal feeds, in fertilisers, bedding, animals, and manure, and is exported in milk products, animals or in crops and manure that are transferred off the farm (Nousiainen et al., 2011). Unlike nitrogen fertiliser, rock phosphate is fairly stable and moves slowly through the soil, therefore the nutrient is available to crops over a number of years and field management can be designed over a whole rotation in order to maintain P at desirable levels in the soil (Defra, 2010). Over application of P can harm beneficial soil organisms, which restricts plant growth and can lead to P losses by means of erosion, run-off, or leaching, where-by P is transferred to surface waters. The resulting anthropogenic eutrophication of lakes and waterways has been described as the worlds’ most prevalent water quality issue (Schindler, 2012).

Despite recent improvements in EU surface water quality (Kristensen, 2012) largely stemming from EU legislation such as the Water Framework and Nitrates Directives

(EC, 2000; EC, 1991), a lack of internationally agreed legislation to account for and manage the application of phosphate fertilisers leads to an absence of common methodologies (Amon et al., 2011) and also a plethora of national measures to regulate phosphate application adopted by individual EU member states (Amery and Schoumans, 2014).

The global dairy industry is growing at 2.2% per year, worldwide consumption of dairy products is expected to rise by 20% by 2021 (IDF, 2014) and as a response to the 2015 dairy quota removal, the UK is among several EU countries planning to increase the output of dairy products (EC, 2013). To service demand, some EU member states have raised milk production (DairyCo, 2014), to supply increasing domestic populations as well develop new markets (EC, 2013; DairyCo, 2014). Dairy industry expansion could lead to intensification as additional animals brought onto established farms would increase herd sizes and therefore manure volumes resulting in environmental challenges.

Livestock systems have a propensity to incur positive P balances (Cuttle et al., 2007), and research has highlighted a variation in nutrient surpluses between farming systems which can be caused by differences in nutrient management techniques rather than farm structure (Brandt and Smit, 1998). Calculating farm nutrient balances and identifying differences across a variety of dairy management regimes can reveal areas of opportunity, to lower environmental impacts, by aiming to optimize nutrient recycling and minimise negative impacts to water (Cooper and Carliell-Marquet, 2013; Mihailescu et al., 2015).

Here we compare P efficiency within novel, intensive and conventional grazing dairy systems across average and improved genetic merits of Holstein Friesian cows by calculating annual farm gate P budgets and applying data envelopment analysis models to test the relative efficiency of the management systems. Nutrient budgets convey farm gate flows and efficacy of P use, whilst the DEA models incorporate further resources such as land requirement and use of nitrogen fertiliser which can characterize the diverse farming systems. We present results generated by multiple application of two types of DEA model, the first of which focuses on the potential polluting aspect of a P surplus by considering residual P as an undesirable output from the milk production system. The second DEA model type reflected the finite nature of P as a resource as well as the potential to pollute by including imported P as an additional non-renewable input variable within the function.

4.3 Methods

4.3.1 Dairy system diets and genetic merit

Production data were obtained from the Langhill herds of Holstein Friesian dairy cows, based at SRUC's Crichton Royal Farm, Dumfries, Scotland. The cows were part of a long term investigation to assess genetic line × feeding system interactions (Pollott and Coffey, 2008). Production and management data were extracted from dairy feed system experiments with the herds being comprised of two distinct genetic lines. The Langhill cows are selected for either increased milk fat plus crude protein (CP) yield (Select line), or they are designated to remain close to an annually established average genetic merit for milk fat plus CP yield for Holstein–Friesians in the UK (Control line) (Pryce et al., 1999; Bell et al., 2011).

Data was drawn from four distinct feeding system trials maintained between 2007 and 2013. During the first comparison (2007 – 2010) cows were given either a low forage (LF) diet consuming an average of 3.0 tons of concentrate annually or a high forage (HF) diet containing approximately 1.2 tons of concentrate (Chagunda et al., 2009). Diets within the second comparison (2011 to 2013) either consisted solely of purchased by-products (BP), or of forage and protein crops grown exclusively on the farm, (HG). The BP and HG regimes can be considered novel as these diet types are unconventional and would not be routinely fed by farmers in the UK.

Forages fed in LF, HF and HG diets included grass silage, maize silage and whole crop wheat silage and Table 4.1 outlines constituents and dry matter proportions of rations with their respective P contents. The HG forages also included lucerne, red clover, spring beans and wheat grain. No forages grown on the farm were included within the BP diets, as these consisted solely of imported feedstuffs (Table 4.1).

Table 4-1 Constituents and dry matter proportions of rations with P contents

Diet	Foodstuff	DM Diet Proportion[e]	DM Content	P Content g/kg DM	P Content (g/day)
By-product	Barley straw	0.23	0.82	1.50[a]	8.00
	Sugar beet pulp molasses	0.21	0.89	1.00[a]	4.90
	Breakfast cereal	0.13	0.91	10.2[b]	30.6
	Wheat distillers grains	0.09	0.28	1.60[c]	3.50
	Biscuit meal	0.09	0.91	3.00[c]	6.00
	Distillers dark grains	0.09	0.91	9.10[b]	18.2
	Soya bean meal	0.09	0.91	6.25[c]	12.5
	Molasses cane	0.06	0.65	1.00[d]	1.30
	Minerals/vitamins	0.01	1.00	60.0[c]	12.0
Low forage	Wheat Grain	0.16	0.88	3.60[b]	13.8
	Sugar beet pulp molasses	0.13	0.89	1.00[a]	3.10
	Soya bean meal	0.12	0.91	6.25[c]	17.6
	Wheat distillers grains	0.06	0.91	9.10[b]	12.2
	Soya hulls	0.02	0.88	1.60[b]	0.90
	Sopralin	0.01	0.85	6.50[c]	2.20
	Grass silage	0.28	0.33	2.80[b]	18.5
	Maize silage	0.09	0.27	2.76[d]	6.10
	Wheat alkalage	0.09	0.67	1.66[d]	3.70
	Minerals/vitamins	0.01	1.00	60.0[c]	15.0
High forage	Grass silage	0.45	0.33	2.80[b]	26.9
	Maize silage	0.15	0.25	2.69[d]	8.60
	Wheat alkalage	0.15	0.65	1.66[d]	5.30
	Rapeseed meal	0.07	0.88	5.60[b]	8.40
	Barley distillers grains	0.11	0.92	3.30[d]	7.60
	Wheat distillers grains	0.06	0.86	9.10[b]	10.9
	Minerals/vitamins	0.01	1.00	60.0[c]	12.0
Homegrown (Winter ration)	Grass silage	0.43	0.26	2.80[b]	25.2
	Spring beans	0.22	0.85	4.90[b]	23.03
	Wheat grain	0.16	0.85	3.60[b]	12.24
	Red clover silage	0.10	0.20	2.40[b]	4.80
	Maize silage	0.05	0.25	2.69[b]	2.69
	Lucerne silage	0.03	0.30	3.00[b]	1.80
	Minerals/vitamins	0.01	1.00	60.0[c]	12.0

[a] Ewing, [b] Feedipedia, [c] Product data, [d] SRUC database, [e]DM = Dry Matter

Each diet was developed to deliver appropriate levels of metabolized energy (ME) and CP for the required maintenance plus a target yield for cows within each of the genetic line × feeding systems. Feeding systems within the groups are defined here as: Low Forage Control (LFC), Low Forage Select (LFS), By-product Control (BPC), By-product Select (BPS), High Forage Control (HFC), and High Forage Select (HFS), Homegrown Control (HGC), and Homegrown Select (HGS).

Groups were managed so that calving took place all year round and each group contained approximately 50 cows being fed a total mixed ration (TMR), approx. 750g of concentrate per cow per day was given in the milking parlour within the HF and LF experiments only. The LF and BP cows were housed all year round (i.e. non-grazing), the HF and HG cows were grazed when there was sufficient available herbage. The HG cows were managed at grass for 2 periods per day and housed for 1 period overnight (approx. 8hrs) whilst feeding on TMR throughout the grazing season. Cows were kept in the herd for at least 3 lactations unless welfare dictated that culling was necessary. In addition cows who failed to conceive after 7 inseminations were removed from the herd.

4.3.2 Data

The dataset compiled in this study consisted of production variables from all cows within the experiments. Variables were extracted from the database for each cow and aggregated annually at group levels. Feeding for the herds was *adlib* and individual feed intakes were recorded for lactating cows when indoors using HOKO automatic feed measurement gates (Insentec BV, Marknesse, The Netherlands). All cows were milked three times a day and samples taken weekly from each of the three milking periods were analysed to provide fat and CP concentrations of the milk.

Production data regarding milk yield, fat and protein concentrations, fertiliser application, herd inventory, land use and diet consumed were extracted directly from the systems database and feed mixer datasheet. Figures for bedding imports were obtained directly from the farm manager (H. McClymont, SRUC, Crichton Farm, Dumfries personal communication). In this analysis, for all herds, heifers were brought into the system at first calving and all calves were assumed to be sold and left the farm. Slurry was not stored separately for each management group and therefore manure volumes for lactating and dry cows were estimated for each system using herd inventory data. Milk yields were expressed in terms of energy corrected milk (ECM) by applying the following formula (Sjaunja et al., 1990) (Equation 1):

$$ECM = 0.25 * \text{Mass of Milk} + 12.2 * \text{Fat (kg)} + 7.7 * \text{Protein (kg)} \quad (1)$$

4.3.3 Dairy system phosphate balances

A farm gate nutrient balance can be defined as a calculation of system inputs and system outputs, where surplus is a positive difference between the total input and output of each nutrient (Table 4.2). Within dairy production, common inputs include feed stuffs fertiliser, purchased animals and bedding and P outputs leaving the farm are found in milk, animals and manure (Table 4.2). Measuring nutrient balances, such the farm gate phosphorus surpluses, is widely used to gauge the potential losses of nutrient to the environment. The phosphorous content in each feed product was taken from the database or from the products themselves and if these were not available from the Feeds Directory (Ewing, 2004) or Feedipedia (Feedipedia, 2015). Quantities of P in milk were estimated using a factor of 0.0093 provided by the Dairy Council (2002). Phosphorus contained within the heifers brought onto the farm system and within animals sold was calculated using an equation based on the weight of animals (Nousiainen et al., 2011) (Equation 2):

$$Phosphorus_{animal}\,(kg) = 0.00067 * Live\ Weight\ (kg) + 0.055 \quad (2)$$

Table 4.2 shows descriptive statistics for variables applied to evaluate annual farm phosphate balances for each of the dairy production systems. Manure production was calculated by determining monthly herd inventory figures for each of the dairy systems and applying liquid and solid manure factors according to milk yield (DairyCo, 2010; Nennich et al., 2005). Estimates for amounts of P contained in slurry and farm yard manure (FYM) were derived from standard values (Defra, 2010). P requirements of crops were taken from the Fertiliser Manual and used to calculate the additional P required (Defra, 2010) to sustain the soil at Index 2, a recommended index, and that which is found in Crichton Royal Farm land. All manure was assumed to be exported from the BP herds because no grazing or crop lands were required within this feeding system.

4.3.1 Data envelopment analysis

To represent each dairy production system at farm level, non-phosphate related variables such as land requirement and nitrogen application were included as inputs within the DEA models. Table 4.3 shows descriptive statistics for non P inputs and outputs common to each system and includes ECM, tonnes of nitrogen, hectares of land and the average number of cows present in each system. Data relating to annual land use for crops and grazing as well as nitrogen fertiliser application within the systems were extracted directly from the database.

Table 4-2 Descriptive statistics of farm gate P balances for each milk production system [ab] (mean and standard deviation)

	LFC		LFS		HFC		HFS		BPC		BPS		HGC		HGS	
Variable	Mean	SD[c]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Input (kg P)																
Feed/Bedding	1466	66.8	1565	82.5	850	54.2	864	90.6	2234	284.5	2456	257.9	821	416	845	441.3
Animals	80.5	15.77	79.4	6.09	80.9	10.31	71.1	16.8	78.5	4.83	82.7	0.84	65.7	23.81	65.9	0.16
Fertilizer	252	48.2	300	50.2	541	62.7	514	88.2	0	0	0	0	943	88.5	1036	149.1
Total Input	1799	120.1	1945	128.1	1472	86.9	1449	179.1	2313	279.7	2538	257.1	1830	480.6	1947	590.3
Output (kg P)																
Milk	469	15.7	524	51.9	396	28.3	431	52.6	437	19.1	513	15.9	336	1.93	366	3.68
Animals	148	14.1	121	9.2	170	24.7	128	18.0	155	23.4	147	9.4	149	30.3	143	11.9
Manure	0	0	0	0	0	0	0	0	518	8.8	582	0.8	0	0	0	0
Total Output	618	22.3	646	60.0	565	43.5	559	67.3	1111	13.1	1242	24.3	485	28.4	508	15.5
P Surplus	1182	134.0	1299	126.6	907	70.9	891	115.3	1203	292.8	1297	232.7	1345	508.9	1439	605.8
P NUE[d]	0.35	0.03	0.33	0.03	0.38	0.03	0.39	0.01	0.49	0.06	0.49	0.04	0.29	0.09	0.29	0.10

[a] Genotype: C = Control, S = Select; [b]Feed systems: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown.
[c]SD=standard deviation, [d]NUE=Nutrient use efficiency

Table 4-3 Descriptive statistics of system [ab] variables applied as inputs within DEA models (mean and standard deviation)

	LFC		**LFS**		**HFC**		**HFS**		**BPC**		**BPS**		**HGC**		**HGS**	
Variable	Mean	SD[c]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Land(ha)	28.8	1.69	29.6	2.43	42.9	1.88	42.7	3.65	0.0	0.0	0.0	0.0	57.2	1.10	59.4	3.40
Nitrogen (tonnes)	3.1	0.12	3.2	0.14	4.7	0.26	4.6	0.12	0.0	0.0	0.0	0.0	4.7	0.08	4.9	0.10
ECM[d] (tonnes)	466	9.16	551	52.9	406	26.8	461	55.5	417	21.5	516	16.6	343	0.51	395	4.79
Avg. Cows	50	0.4	47	3.7	54	1.1	52	3.1	55	2.5	48	1.0	59	0.0	54	1.0

[a] Genotype: C = Control, S = Select; [b] Feed systems: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown
[c] SD=standard deviation, [d] ECM=energy corrected milk

Data envelopment analysis (DEA) is a method used to estimate the efficiency of production systems based on the assumption of optimizing behaviour, namely it provides a way of analysing the degree to which producers fail to optimize and the extent of the deviations from technical and economic efficiency (Färe et al., 1994). Pitman (1983) extended the traditional efficiency analysis to account for undesirable outputs (*e.g.*, pollutants associated with agricultural emissions from dairy farms) by estimating efficiency measures that allow for the asymmetric treatment of desirable and undesirable outputs (desirable outputs are strongly disposable as it is always possible to reduce the production of a desirable output without increasing costs; undesirable outputs are weakly disposable as it is not possible to reduce the production of an undesirable output without reducing the production of a desirable output or increasing the use of an input). Since then several DEA modelling approaches have been developed for environmental efficiency measurement (Färe et al., 1996; Piot et al., 1995; Tyteca, 1996; Kuosmanen and Kortelainen, 2005; Kortelainen, 2008). Additionally, DEA approaches have been developed for the specific treatment of those inputs which can be viewed as valuable resources (e.g. non-renewable resources such as phosphorus) whose uptake can exert a threat on the environment. Some of these modelling approaches consider both non-renewable resource inputs and undesirable outputs (Tyteca, 1996, Korhonen and Luptacik, 2004; Liu et al., 2006; Bian et al., 2010; Bi et al., 2012).

This paper estimates two DEA models, one to consider the treatment of phosphorus as [an] undesirable output (undesirable output-orientated model (UO)) and the other incorporating phosphorus as both undesirable output and non-renewable input (input-undesirable output-orientated model (IUO) model) (Tyteca, 1996).

The Nonparametric Undesirable Output-Orientated Model (UO) is as follows:

$$\text{minimise } T \quad (T \leq 1) \qquad (3)$$

$$\text{subject to} \quad \sum_{k=1}^{K} z^k v_m^k \geq v_m^0 \,, \qquad m = 1, \ldots, M$$

$$\sum_{k=1}^{K} z^k w_j^k = T w_j^0 \,, \qquad j = 1, \ldots, J$$

$$\sum_{k=1}^{K} z^k x_n^k \leq x_n^0 \ , \qquad \text{n= 1, ..., N}$$

$$z^k \geq 0 \ , \quad \text{k= 1, ..., K}$$

Where:

M, J, and N are the numbers of desirable outputs, inputs, and undesirable outputs, respectively; K is the number of observations (producers, time periods, or in our case, dairy systems by year and treatment); v_m^0, w_j^0, x_n^0 are desirable outputs, undesirable outputs and inputs, respectively. In the case of observation 0, observation 0 $\in \{1,...,K\}$ takes values from 1 to K, successively. Variable T represents the standardized indicator of environmental performance; variable Z is a vector which denotes the intensity levels at which each of the K observations are conducted, enables shrinking or expanding individually observed activities for the purpose of constructing unobserved but feasible activities, and provides weights which facilitate the construction of the linear segments of the piecewise linear boundary of the technology.

The model shows one key difference to the classical DEA formulation, namely that instead of minimizing a ratio of inputs to outputs or maximizing a ratio of outputs to inputs, it minimises a ratio of undesirable outputs to a weighted sum of desirable outputs and inputs. Thus the undesirable outputs are considered as peculiar outputs which one tries to minimise with respect to the other factors of production (inputs and desirable outputs) (Tyteca, 1996):

$$\text{minimise} \quad h_0 = \frac{\sum_{j=1}^{J} c_j w_j^0}{\sum_{m=1}^{M} a_m v_m^0 - \sum_{n=1}^{N} b_n x_n^0} \qquad (4)$$

$$\text{subject to} \quad \frac{\sum_{j=1}^{J} c_j w_j^k}{\sum_{m=1}^{M} a_m v_m^k - \sum_{n=1}^{N} b_n x_n^k} \geq 1 \ , \text{ k = 1, ..., K}$$

$$a_m, b_n \geq 0 \ , \ c_j \text{ free}$$

where h_0 represents the standardized indicator of environmental performance; and a_m, b_n and c_j denote intensity levels.

The model assumes constant returns to scale, *i.e.*, in pollution terms, for efficient decision making units (DMU), namely those showing a value of T equal to 1, a given increase in desirable outputs and/or inputs would result in a proportional increase in undesirable outputs (Färe, 1992).

The input—undesirable output-orientated model (IUO) is a variant of the nonparametric undesirable output-orientated model (UO) and is as follows:

$$\text{minimise } h_0 = \frac{\sum_{n=1}^{N} b_n x_n^0 + \sum_{j=1}^{J} c_j w_j^0}{\sum_{m=1}^{M} a_m v_m^0} \qquad (5)$$

$$\text{subject to} \quad \frac{\sum_{n=1}^{N} b_n x_n^k + \sum_{j=1}^{J} c_j w_j^k}{\sum_{m=1}^{M} a_m v_m^k} \geq 1 \text{ , } k = 1, ..., K$$

$$a_m, b_n \geq 0 \text{ , } c_j \text{ free}$$

The model minimises the ratio of a weighted sum of inputs and undesirable outputs over the desirable outputs. From an environmental performance viewpoint, this means that firms likely to operate near points where output productivity (ratio of inputs to desirable outputs) is optimal will be differentiated as regards environmental performance and the most environmentally efficient firms will show the smallest possible ratio (i.e. 1) while the less environmentally efficient firms will be prevented from reaching the frontier (Tyteca, 1996). This model is suitable for the treatment of those inputs which can be considered as valuable resources (e.g. non-renewable resources) (Tyteca, 1996, Korhonen and Luptacik, 2004; Liu et al., 2006; Bian et al., 2010; Bi et al., 2012).

A number of research papers analyse system efficiency using various DEA methods depending on the way nitrogen use or phosphorus use variables are incorporated in the models (Reinhard et al., 2000; Ondersteijn et al., 2001; Coelli et al., 2007; Barnes et al., 2009; Picazo-Tadeo, 2011; Molinos-Senante et al., 2011; Hoang and Alauddin, 2012; Toma et al., 2013) and comparing different farming systems, in some cases dairy farms (Reinhard et al., 2000; Ondersteijn et al., 2001; Barnes et al., 2009; Toma et al., 2013). To the best of our knowledge, our paper is the first to analyse phosphate efficiency of dairy systems using the models detailed above.

Ten models were estimated, namely: four undesirable output-orientated (UO) models, (where undesirable outputs were phosphate surplus), and six input-undesirable output-orientated (IUO) models, (where undesirable outputs were phosphate surplus and non-renewable resource inputs were phosphorus in feed, fertiliser, straw bedding and also that contained within the bones and tissues of animals entering the herd). Included in all models were land and nitrogen fertilisers as inputs, and phosphorus in milk, phosphorus in animals sold and phosphorus in manure exported as desirable outputs.

In building the relative environmental efficiency measure, we use the DEA endogenous weighting scheme (Farrell, 1957; Charnes et al., 1978; Tyteca, 1996). We estimated the models using the General Algebraic Modelling System (GAMS 22.8). We used DEA to account for temporal aspects, *i.e.*, not only to compare the dairy systems amongst themselves, but to quantify changes in environmental efficiency over time. The models consider each of the systems as divided into a number of independent DMUs, namely four annual observations each for LFC, LFS, HFC and HFS respectively and two annual observations each for BPC, BPS, HGC and HGS. This follows a similar approach used by Färe et al., 1996; Ball et al., 1994 and Toma et al., 2013 and results in a set of 24 DMUs. Thus, the best practice production frontier is composed of systems that were efficient in any of the years considered. The analysis allows us to provide a measurement of improvement (or deterioration) in environmental efficiency for each system over time.

4.4 Results

4.4.1 Dairy systems production differences

Across feed systems, mean milk sales were highest from the Select genotype within the continuously housed LF and BP groups, which produced an average of 551,852 kg/system/year and 516,105 kg/system/year respectively. The lowest milk output stemmed from the HGC system which produced 343,753 kg / system / year on average (Table 4.3). The need for ‘on farm’ land varied between systems, with the greatest mean land area of 59.4 ha being required by the HG system. Select cows consistently yielded more than the Control line, and within systems, Select cows required slightly more food and hence land because feed intakes were higher. Land, nitrogen fertiliser and home-grown feeds were a feature of all feed groups apart from the BP system (Table 4.3). The BP system imported an average of 641 tons / year of fresh weight purchased feeds and bedding whereas the least imports arose from the HG system which required 68.9 tons / year on average. Foodstuff imports for the HG system arose from a shortage of farm grown beans and wheat, however supplements such as minerals and magnesium chloride are required to be imported in all systems. Compared to other management regimes there was little difference between the Select and Control cow yields within the HG diets, which could be due to dietary factors such as the quality of grazed grass or forage within the ration.

4.4.2 Farm phosphate budgets

When evaluating absolute quantities of surplus P among all feed systems, lowest amounts of excess nutrients were generated from the HF groups because P feed input was minimal, and on average, P exports were proportionally higher. Higher fertility rates within the grazed systems resulted in fewer heifer imports and a greater number of calves leaving the system. Highest quantities of surplus nutrient arose mainly from the BP and LF feed systems because much larger amounts of P were imported within purchased feeds. Even though all manure was exported from the BP system it was insufficient to offset imports of P (Table 4.3). The HG systems attracted a higher P surplus in 2012 as imported feed P was greater than anticipated which highlights the prospect of variable establishment costs relating to this system due to local climates.

On average, system P Nutrient Use Efficiency (NUE) (represented by P outputs divided by inputs), was found to be greatest within the BP group (0.49) because all manure was exported from the farm (Table 4.2). The HF feed group averaged 0.39 NUE and this conventional grazed system was more P effective than an intensive housed LF management regime feeding large amounts of concentrates combined with farm grown forages. Within the feed systems, Control cows generally consumed marginally less feed and exported less milk than Select groups, however there was little difference between each systems' average P NUE.

When production of energy corrected milk (ECM) is considered, between all systems, per litre surpluses ranged from 0.002 to 0.005 kg P/ litre. On average a UK conventional HF feeding system generated the lowest average surplus of 0.002 kg ± 0.0003, whilst the HG feed system attracted the highest average surplus of 0.004 ±0.002 kg P per litre of ECM because of a poor establishment year. Within each feeding system, on average, cows of Select genetic merit always generated less surplus P per litre of ECM than cows of an average UK merit.

4.4.3 Data envelopment analysis

Two distinct types of DEA model were applied to assess any differences emphasis regarding the P resource. Efficiency scores generated by an undesirable output orientated model as well as an input undesirable output orientated model were calculated. The undesirable output model assesses the ability of each system to produce milk whilst considering environmental externalities whereas the input undesirable output model considers externalities and also reflects the non-renewable nature of the resource. Four and six runs respectively of each model type generated annual efficiency scores for each system depending on the nature of variables included in the models (Tables 4.4 & 4.5).

Table 4-4 Dairy system [ab] efficiency scores for undesirable output (UO) data envelopment analysis models

Year	System	UO1	UO2	UO3	UO4
2007	LFC	0.62	0.575	0.51	0.325
2008	LFC	1	1	0.787	0.484
2009	LFC	1	1	1	0.495
2010	LFC	0.794	0.811	0.703	0.453
2007	LFS	0.618	0.536	0.526	0.316
2008	LFS	0.902	0.839	0.81	0.477
2009	LFS	1	1	1	0.487
2010	LFS	1	1	1	0.592
2007	HFC	0.802	0.665	0.626	0.373
2008	HFC	1	1	0.569	0.381
2009	HFC	1	1	1	0.575
2010	HFC	1	1	0.64	0.428
2007	HFS	0.944	0.782	0.782	0.416
2008	HFS	0.823	0.741	0.741	0.425
2009	HFS	1	1	1	0.498
2010	HFS	1	1	1	0.57
2012	BPC	0.774	0.687	0.679	0.588
2013	BPC	1	1	1	1
2012	BPS	1	1	1	0.773
2013	BPS	1	1	1	1
2012	HGC	1	1	0.233	0.146
2013	HGC	1	1	0.792	0.361
2012	HGS	0.331	0.269	0.233	0.153
2013	HGS	1	1	1	0.408

[a] Genotype: C = Control, S = Select

[b] Feed system: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown.

Table 4-5 Dairy system [ab] efficiency scores for input undesirable output (IUO) data envelopment analysis models

Year	System	IUO1	IUO2	IUO3	IUO4	IUO5	IUO6
2007	LFC	1.00	0.98	0.95	1.00	1.00	0.69
2008	LFC	0.94	1.00	0.93	0.77	0.76	0.75
2009	LFC	1.00	1.00	1.00	0.78	0.75	0.74
2010	LFC	0.94	0.98	0.92	0.72	0.71	0.71
2007	LFS	0.91	0.91	0.91	0.69	0.67	0.63
2008	LFS	0.97	0.96	0.96	0.71	0.69	0.69
2009	LFS	1.00	1.00	1.00	0.74	0.68	0.68
2010	LFS	1.00	1.00	1.00	1.00	1.00	0.65
2007	HFC	1.00	0.96	0.94	0.97	0.90	0.91
2008	HFC	0.82	1.00	0.85	0.90	0.86	0.87
2009	HFC	1.00	1.00	1.00	1.00	0.94	0.85
2010	HFC	0.89	1.00	0.85	1.00	0.86	0.85
2007	HFS	1.00	1.00	1.00	1.00	1.00	0.95
2008	HFS	0.96	0.93	0.93	0.86	0.82	0.80
2009	HFS	1.00	1.00	1.00	1.00	0.83	0.81
2010	HFS	1.00	0.99	0.99	1.00	1.00	0.75
2012	BPC	1.00	1.00	1.00	1.00	1.00	1.00
2013	BPC	1.00	1.00	1.00	1.00	1.00	1.00
2012	BPS	0.87	0.91	0.91	1.00	0.81	0.83
2013	BPS	1.00	1.00	1.00	1.00	1.00	1.00
2012	HGC	1.00	1.00	1.00	1.00	1.00	1.00
2013	HGC	1.00	1.00	0.95	1.00	1.00	1.00
2012	HGS	0.73	0.80	0.80	0.78	0.72	0.78
2013	HGS	1.00	0.97	0.91	1.00	1.00	0.91

[a] Genotype: C = Control, S = Select

[b] Feed system: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown.

4.4.4 Undesirable output model – potential to pollute

Across all years and models, average efficiency scores ranged from 0.55 within HGS to 0.97 within BPS, with the highest to lowest average system scores being BPS>BPC>HFS>LFS>HFC>LFC>HGC>HGS. Factors in the BP management regime, i.e. manure exportation, no requirement for crop land, grazing pasture or fertilisers have merged to benefit this feed system. However, Select cows within a more conventional grazed HF system had the potential to be almost as efficient, because imported feed P was much lower comparatively. Select cows were generally more efficient in each feed system, apart from HG which was the lowest yielding system.

Results showed a wider range of scores within the HG feed systems which are reliant on local weather conditions for crop production. Lower scores in 2012 are attributed to poorer than expected crop yields caused by a season of higher than average rainfall which hindered the establishment of lucerne and also affected other crops. Lower end efficiency scores obtained within the LF feed systems stemmed from a proportionally higher P input from purchased feeds and lower P outputs from milk yield in 2007 (Table 4.3). All systems except BP 2013 were found to be less efficient using Model 4 (Table 4.4) which could be because the various P input and P output variables are aggregated within this model (Table 4.4).

4.4.5 Input undesirable output model - Pollution potential and finite resource

Efficiency scores across all years ranged from a low of 0.85 in the LFS system, to 1.0 within the BPC and HGC systems, with the next most efficient systems being the BPS and HFS management regimes (Table 4.5). When non-renewable properties of the P resource were considered, average efficiency scores increased across all six models which could reflect the nature of formulated rations. Overall increases in comparative efficiency scores across the board are likely to have occurred as a result of the fact that diets formulated for each of the systems are tailored to meet the energy and protein needs of the animals and thus excess inputs should be minimal.

Even though the BP system again attained the highest average efficiency score, in this case, a HG system was found to be comparatively just as efficient. This could highlight that farmers adopting housed systems importing large amounts of purchased P within feeds are not practicing feeding regimes that adopt minimal inputs of the resource with least surplus to the environment. When comparing efficiency of genetic merits between the IUO models, within the different feed systems, on average, Select cows were less efficient than Control cows. This may suggest that higher feed P intakes of Select groups has not equated directly to sufficient increases in the outputs of P in milk. Greater P intakes of the heavier Select cows do not seem to be required for animal maintenance or milk production.

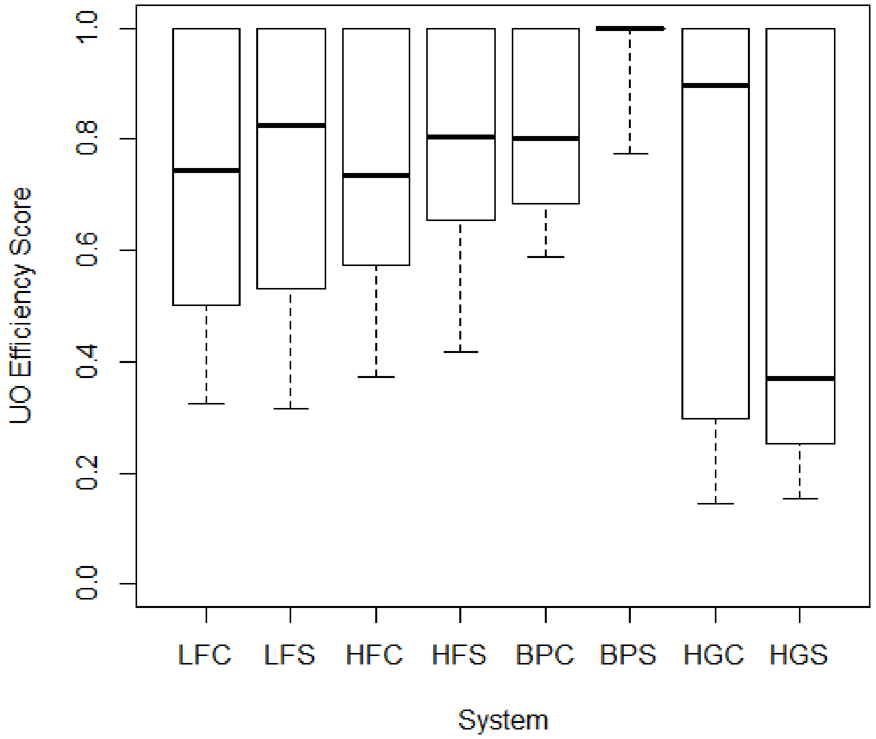


Figure 4.1 Boxplots of undesirable output (UO) model average efficiency scores, showing range and median for each system [ab]

[a] Genotype: C = Control, S = Select
[b] Feed system: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown.

4.5 Discussion

Comparing the efficiency of phosphorus use within novel, intensive, and conventional dairy systems across two genetic merits of Holstein Friesian dairy cows by focusing on both the potential to pollute and also the finite nature of the resource, shows that alternate management regimes can be perceived to be more efficient depending on the emphasis of the DEA model. When accounting for the potential to pollute, Figure 4.1 illustrates that Select genetic merit cows are generally more ecologically efficient than those of an average merit, which could be expected because of greater volumes of milk production combined with improved nutrient utilization. When potential losses of P to the environment are considered, a conventional grazing system with limited purchased feed inputs can be comparatively more efficient than a continually housed high concentrate approach, importing large amounts of purchased feeds as well as growing forages.

Farms that exclusively bring in non-human edible by-products and have the added ability to export manure are found to be more P efficient than a grazing system with low imported feeds. This is because P outputs leaving the farm boundary are greater, and this would be desirable as long as the exported manure P is applied to land within a reasonable geographical distance and utilised as a replacement for imported rock phosphate. Traditionally, UK dairy farms are concentrated in westerly regions, favourable for grass growing. Whilst it is accepted that a BP system would not be collectively desirable, crop growing agricultural areas requiring high imports of purchased P within range of by-product feed sources may value a local supply of manure.

When pollution potential is included alongside an additional prominence of inputs of P into the systems, to represent the finite nature of the resource, animals within more conventional grazed regimes, supplemented with home-grown feeds or low amounts of purchased concentrates, can be, on average, as efficient, or do not differ greatly in efficiency from the confined systems. Across the Input Undesirable Output model scores averaged in Figure 4.2, efficiency scores derived from animals of an average UK genetic merit are comparable to improved merit Select cows. This could be because the difference in P inputs for Select animals is not reflected in the P outputs, so the extra feed P is not fully required for maintenance, lactation or gestation and hence is likely to be excreted.

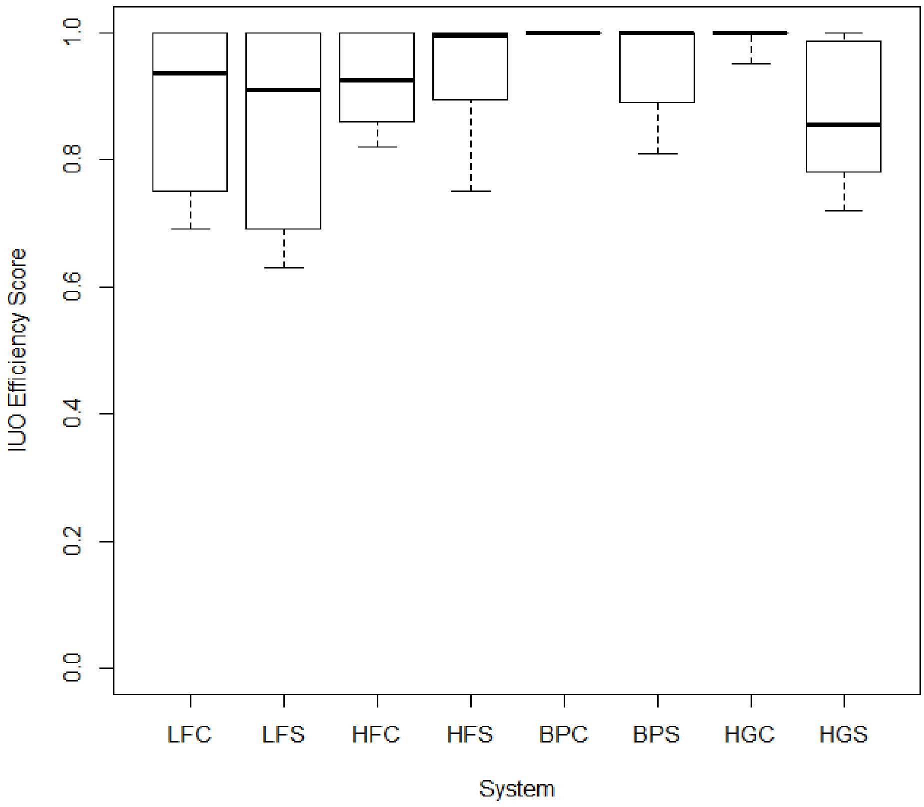


Figure 4.2 Boxplots of input-undesirable output (IUO) average efficiency scores, showing range and median for each system [ab]

[a] Genotype: C = Control, S = Select
[b]Feed system: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown.

High P excretion would not be unexpected as a dairy cow could be described as an inefficient consumer of P because these animals can excrete up to 70% of their P intake (Ferris et al., 2010; Nennich et al., 2005) and a direct relationship exists between P intake and P in faeces (Morse et al., 1992; Kebreab et al., 2005). A dairy cow absorbs a varying amount of P depending on her stage of lactation and gestation (NRC, 2001), and endogenous processes further inflate P excretion to faeces (Guegen et al., 1988). In the UK, calls have been made to re-evaluate outdated feeding standards for mineral requirements such as P because the objective of production has shifted to human health and the environmental effects (McDonald et al., 2011). Total mixed rations with *ad lib* feeding systems formulated to meet major nutrient requirements could over supply minerals to cows with higher intakes.

Whilst deficiencies of dietary phosphate can be associated with health issues such as reduced fertility, recent experiments have shown that feeding less P to dairy cows resulted in lowered faecal P output (Ferris et al., 2010). Opportunities exist to lower the amount of P consumed as a percentage of dry matter intake, lowering overall use via a reduction in dietary intake, and thus resulting in less P entering waterways as less is excreted. Farmers may tend to apply maximum rates of fertiliser to increase crop yields and may also utilise higher levels of concentrate feeds when costs are relatively low and milk prices are high. Therefore, more efficient use of nutrients such as phosphorus may not generally drive management decisions.

The farm gate P balance can be described as a broad indicator of losses to aquatic systems and is equivalent to the OECDs gross balance, with the addition of bedding imports (Amon et al., 2011). A soil phosphate balance may give a more representative indication of environmental losses however the data required necessitates estimations associated with greater uncertainty than the Farm Balances applied here. Nutrient use efficiencies (NUE’s) presented here are comparable with estimates reported from similar dairy systems (Gourley et al., 2012; Defra, 2011). NUE results ranged from 0.19 to 0.55 (Table 4.2) and surpluses per hectare ranged from 14.9 kg P in a HGS system to 48.1 kg P in a LFS system (Table 4.2 and Table 4.3). However, lack of required crop land in the BP system renders a per hectare unit obsolete and high surpluses per hectare stemming from LF systems would be expected due to no necessity for grazing land. Intensive grazing systems, with lower than UK average yields per cow (circa 5000 litres per annum) tend to attract higher NUE’s and a lower P surplus per hectare. NUE means of 0.71 and surpluses of 4.93 kg P/ha were reported from a study of nineteen dairy farms in Southern Ireland adopting grass based low input dairy systems (Mihailescu et al., 2015). A surplus median of 28 kg P/ha was found across a range of Australian dairy farming systems (Gourley et al., 2012) which compares with a median surplus of 27 kg P /ha found in this analysis.

Calculating nutrient balances and the potential for losses to the environment provides a gauge of farm system efficiency (Jarvis and Arts, 2000; Mihailescu et al., 2015, Thomassen and De Bour 2005) and can assist management decisions (Halberg, 1999). Nutrient budgets expressed in this paper provide a range of P efficiencies and surpluses per litre of ECM, depending upon the genetic merit of an animal within a particular dairy feeding system. Generic procedures could be adopted to calculate and compare nutrient losses so as to inform future strategies for nutrient regulation and mitigation. Specific coefficients could be recommended based on current research; various factors of P output within milk can be applied and manure P content may differ between intensive and grazed systems which could influence P surplus calculations. For example, milk samples from the BP system were analysed and P content ranged from 850 to 1169 mg/kg (Pers. Comm., Alan Sneddon).

Differences in model results presented here outline the importance of emphasis within analytical techniques when considering non-renewable resources such as phosphorus. P budgets highlight the potential for efficiency gains, attained by manure recycling within localized protein crop growing regimes, or by exportation to other agricultural systems within an economically feasible range. These results could support efficiency approaches incorporating more cyclical nutrient management, which can reuse, and recycle P, within livestock systems (EC, 2014; Buckwell et al., 2014). The results may also assist those appealing for an increased understanding of mutually beneficial adaptation techniques that improve environmental performance in a practical, economically viable manner (Ulrich & Frossard, 2014).

Whilst the EU Nitrates and Water Framework Directives (EC, 1991; EC 2000) indirectly regulate agricultural P applications to soils, and even though national and regional legislation is implemented across member states, these are not legally binding. Countries such as Denmark, Ireland and the Netherlands have implemented restrictions on P application, depending on variables such as soil type and crop requirements, whereas farmers in England or Hungary have no additional restrictions (Amery and Schoumans, 2014). Close attention to appropriate livestock nutrient requirements alongside on farm soil P status and combined with mitigation methods such as buffer zones may bring about improvements in surface water quality (Schindler, 2012).

Ulrich and Frossard (2014), argue that persistent debate regarding resource scarcity should shift towards a comprehensive understanding of the environmental and economic consequences of prolonged utilization of P. Calls to improve unsustainable food production methods (Foresight, 2011) have furthered a discussion of the environmental benefits of high input (Ross et al., 2014) and low input dairy systems (O’Brien et al., 2012a; Casey and Holden, 2005). Results expressed here show that when one pollutant is considered, model emphasis alters perceived system efficiency. Depending on the focus of sustainability, whether it be phosphorus, nitrogen, greenhouse gases, or ammonia emissions, intrinsic qualities and weaknesses seem apparent within dairy management regimes. National dairy farming regimes are likely to be a function of history, demand, culture and regional climate.

Working towards closed loop farming systems is a feature of organic (Steinshamn et al., 2004) and biodynamic dairying, and techniques to reuse P can be developed using model budgets. A combination of HG and BP systems may have the ability to generate a dual production regime in which P is recycled from a confined system feeding by-products (inedible to humans) with negligible land requirement, to a regime feeding a selection of farm grown protein crops to complement grazing. Manure P exported from a BP system could be utilized within an HF, HG or other low input system, thus reducing the need for imported fertiliser, manure exportation and employing a system that is not solely reliant on either purchased feeds or local weather.

Of all the essential dietary minerals required by dairy cows, an excess of P poses the greatest risk to the environment (NRC, 2001). Planned dairy sector development across the EU leading to increases in milk production, could propel trends towards larger herd sizes (DairyCo, 2014) as well as modifications in feeding practices. Crops grown in the UK are dependent on imported phosphorus, amounting to 138 kilo tonnes in 2009 (Cooper and Carliell-Marquet, 2013) and it’s estimated that up to 80% of extracted rock P is potentially lost from mine to food to fork (Childers et al., 2011).

Understanding and improving resource use efficiency whilst minimizing undesirable outputs are crucial steps to achieving more sustainable milk production. Further research comparing the merits of alternate farming systems, taking into consideration resources such as water, and pollutants such as greenhouse gas emissions, would benefit the overall understanding of the merits of each management regime.

4.6 Conclusion

The purpose of this paper was to evaluate and compare phosphorus efficiency within novel, intensive and conventional dairy systems across two genetic merits of Holstein Friesian cows by application nutrient budget calculations and dual DEA model types. Undesirable output orientated models showed that, on average, cows selected for improved production within a By-product system exporting all manure attracted the highest NUE's and DEA efficiency scores. However, a low concentrate input grazing system generated the lowest per litre P surplus and efficiency scores were higher than confined feeding systems that did not export manure. Input undesirable output orientated models did not always favour the Select improved genotype and the lower input Home-grown and High Forage feed systems were most efficient. Nutrient budget estimates of dual systems highlighted possibilities to reuse and recycle P. Results presented here raise questions regarding suitable pathways to be taken by policymakers, industry stakeholders and farmers to achieve optimal use of phosphorus with minimal surplus to the environment.

4.6.1 Additional information

A total of ten models were estimated and a description of variables included for each model is provided in Tables 4.6 and 4.7. Four undesirable output-orientated (UO) models considered P surplus as an undesirable output, and six input-undesirable output-orientated (IUO) models undesirable output was P surplus, and the non-renewable resource inputs were P imported into the farming systems in fertiliser, feed, and also an estimate of P contained within the bones of animals entering the herd. Models also included land area and nitrogen fertilisers as inputs. P exported in milk, in animals sold and in manure as were considered as desirable outputs.

Table 4-6 Variables applied in respective input undesirable output orientated (IUO) models

	Model 1	Model 2	Model 3	Model 4
Inputs	Fertiliser P kg Feed P kg Cows kg Land ha Nitrogen kg	Fertiliser P kg Feed P kg Cows kg Land ha Nitrogen kg	P Input Total kg Land ha Nitrogen kg	P Input Total kg
Desirable Outputs	ECM P kg Animal P kg	P Output Total kg	P Output Total kg	P Output Total kg
Undesirable Outputs	P Surplus kg / kg ECM	P Surplus kg / kg ECM	P Surplus kg / kg ECM	P Surplus kg / kg ECM

ECM = Energy corrected milk

Weighting of production factors within the DEA models was endogenous and driven by the data. This meant there was no need to consider the pricing of public goods. Pricing of public goods can be subjective as the cost of pollution potential may be difficult to quantify.

Table 4-7 Variables applied within input undesirable output orientated (IUO) models

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Inputs	Land ha Nitrogen kg		Land ha Nitrogen kg	Land ha Nitrogen kg		Land ha Nitrogen kg
Non-renewable Inputs	Fertiliser P kg Feed P kg	Fertiliser P kg Feed P kg	Fertiliser P kg Feed P kg	P Input Total kg	P Input Total kg	Fertiliser P kg Feed P kg
Desirable Outputs	ECM P kg Animal P kg	ECM P kg Animal P kg	P Output Total kg	P Output Total kg	P Output Total kg	ECM P kg Animal P kg
Undesirable Outputs	P Surplus / kg ECM	P Surplus / kg ECM	P Surplus / kg ECM	P Surplus / kg ECM	P Surplus / kg ECM	P Surplus (kg)

ECM = Energy corrected milk

Chapter 5

5 Modelling the effect of feed and allocation method on the carbon footprint of diverse dairy management systems

5.1 Summary

The livestock industry urgently needs to reduce greenhouse gas (GHG) emissions in order to contribute to ambitious climate change targets. Achieving this requires an improved understanding of emission sources across a range of production systems in order to lower the burden associated with livestock products. This chapter models the range of dairy feeding systems to quantify the effect of feed component allocation method and management regime on emission types and totals. Natural variation in nutritional quality of dairy system rations on GHGs emitted in the production of milk is investigated to quantify uncertainty in the footprint results. Carbon footprints from two genetic lines of Holstein Friesian cows managed in two novel and two conventional UK dairy feeding regimes are presented using life cycle assessments. Average merit footprints across each of the management regimes were significantly higher ($p<0.001$) in comparison with a high production merit, on average by 15%. Livestock and embedded emissions were also significantly higher from control merit cows ($p<0.01$). Mass and economic allocation methods, and land use functional units, resulted in differences in performance ranking of the dairy systems, with mass allocation footprints increasing. Pairwise comparison tests showed GHGs from the systems to be significantly different in totals and type with significant differences in mean embedded emissions found between all management systems ($p<0.05$). Monte Carlo simulated system footprints considering the effect of variation in feed digestibility and crude protein also differed significantly from system footprints using standard methods ($p< 0.001$).

5.2 Introduction

The Climate Change Act requires the UK to meet a legally binding target of an 80% reduction of GHGs by 2050, when the country should be emitting no more than 156 Mt CO_2e (HMSO, 2008). More recently Scotland has adopted an even more ambitious target of reaching net-zero emissions by 2045 (Scottish Government (SG), 2018). Agriculture is estimated to be responsible for 10-12% of greenhouse gas (GHG) emissions globally, with 2.7% attributed to the production of milk (Smith et al., 2014; Gerber et al., 2010). In countries such as the UK and in Western Europe GHG emissions stemming from milk production are estimated at between 1.2 and 1.4 kg CO_{2e} /kg respectively which is lower than the global average of 2.5 kg CO_{2e} /kg (FAO, 2018; AHDB, 2014). Dairy products have been processed and consumed in Britain since the Neolithic era and grassland, including rough grazing, covers approximately 80% of the land area in Scotland. However, agriculture is now the second largest source of GHG emissions in Scotland, there is an urgent need for this sector to contribute to national GHG emission reductions (Charlton et al., 2019; SG, 2016). GHG emissions associated with Scottish milk production were estimated to be 1.4 Mt which represented 2.5% of Scotland's total emissions reported in 2011 (Sheane et al., 2011). However, GHG emissions from livestock need to be reduced at a time when global demand for these commodities is increasing (Opio et al., 2013; Alexandratos and Bruinsma, 2012).

UK GHG emissions from agriculture have declined by approximately 14% since 1990, and reductions have largely arisen from a change to the Common Agriculture Policy (CAP), which ended a link between subsidy amounts and animal numbers (DBEIS, 2019; AHDB, 2014). An increase in average UK milk yields and improved farm nitrogen use efficiencies have contributed towards reductions in emission intensities. Fewer total livestock numbers have led to lower stocking densities, less manure and thus lower emissions generated (DBEIS, 2015; del Prado et al., 2010; Rotz, 2004). Models used to quantify GHGs are important tools to aid the understanding of mitigation pathways that lie within the intricate footprints of livestock systems (Opio et al., 2013). Formulating policies to enable further emission reductions on dairy farms will require an understanding of mitigation measures appropriate for specific production systems.

Estimates of GHG emissions from livestock systems contain uncertainties from model boundaries and allocation, variation in input values, or epistemic uncertainty arising from modelled biological processes, all these uncertainties present challenges for researchers and decision makers (IPCC, 2006; Flysjö et al., 2011; Opio et al., 2013; Röös and Nylinder, 2013). Epistemic uncertainty (i.e. uncertainty brought about by modelling a biological system) of dairy and beef livestock systems have shown that, overall, nitrous oxide (N_2O) and methane (CH_4) emissions from manure, fertiliser N input, and enteric CH_4 contribute most to variability (Zehetmeier et al., 2014; Ross et al., 2014; Sykes et al., 2019). Methodologies to model CH_4 and N_2O emissions from manure, and enteric CH_4 require measurements of diet digestibility and crude protein (CP) (Dong et al., 2006). Diet digestibility has been shown to influence uncertainty in beef production footprints (Sykes et al., 2019). Digestibility effects enteric CH_4 production through fibre in the diet and protein effects urinary N and subsequent ammonia emissions which can effect N_2O from manure (Wattiaux et al., 2019). The consequences of dietary and other variabilities should be considered, and uncertainties communicated when quantifying dairy farm carbon footprints (Zehetmeier et al., 2014; Milne et al., 2015).

The digestibility of a dairy cow diet relates to the chemical composition of feed components, and the ration as a whole. Digestibility can be described as the fraction of a food that is absorbed, and this is effected by fibre content of feeds, of which the forage components tend to exhibit wider variation (McDonald et al., 2013). Predictions of enteric CH_4 emissions are lower from diets with high digestibility (Röös and Nylinder, 2013). Lower digestibility of a ration can lead to reduced nutrition per kg of dry matter intake (DMI) which may necessitate greater feed intakes to meet an animals requirements (Dong et al., 2006). Rations containing optimum digestibility and balanced CP can lead to lower GHG emissions because a cow would require less feed to meet nutritional requirements, however efficiency of feed conversion and DMI of the animal are the main factors determining enteric CH_4 (Wattiaux et al., 2019).

Too much CP leads to higher N excretions, which can cause nutrient surpluses that contribute to air and water pollution, as well as climate change (Chadwick et al., 2018; IPCC, 2006). In comparison with soybean meal legumes such as faba beans and peas in a ration were shown to have higher digestibility, CP and energy, which can be beneficial within dairy cow rations as they degrade rapidly in the rumen (Volpelli et al., 2012). Dairy cow rations including legumes should be balanced to ensure higher levels of CP do not reduce NUE.

Legumes are found in a wide range of ecosystems and the majority are genetically distinct form other plant species due to a symbiotic relationship with rhizobia. These are soil bacteria located within root nodules with the ability to fix nitrogen from the atmosphere (Kenicer, 2005). Within crop rotations, legumes can displace the need for imported nitrogen fertilisers, as well as nurture and condition the soil which can have positive environmental and resource security consequences along with disease suppressing qualities (Stagnari et al., 2017; Luscher et al., 2014). Home-grown protein feeds for animal production are increasingly being encouraged in the EU to reduce the protein deficit that relies upon soya imports which can fluctuate in price and can be associated with rainforest loss (Taherzadeh & Caro 2019; EU, 2018). Introducing legumes such as spring beans into crop rotations has the potential to reduce emissions through displacement of fertilisers, which in Scotland would translate to 100 to 180 kg/ha per year for spring and winter cereals respectively (Iannetta et al., 2019). Legumes are estimated to generate less than 20% of emissions associated with synthetic fertilisers, however N_2O emissions can occur from leguminous crop residues (Stagnari et al., 2017; Senbayram et al., 2015). An increase in the use of forage legumes within dairy systems should therefore be considered to improve outcomes for livestock and the wider environment.

This paper seeks to clarify the impact of dairy systems on the environment using a modelling approach to address specific questions; (i) what affect does the method of allocation of emissions from animal feeds in dairy systems have on the footprint of milk produced, (ii) what effect does alternative system inputs, such as legumes and by-product have on the composition of carbon footprints and (iii) what is the effect of variation in feed digestibility and CP content on the global warming potential of milk produced in dairy systems under a range of management scenarios. Carbon footprints from Holstein Friesian cows managed in novel and conventional UK dairy feeding regimes are presented using life cycle assessment (LCA) methods. Monte Carlo simulation were applied to describe uncertainty brought about by variation in nutritional quality of the diets. Mass and economic allocation of feed components and land use functional units generate alternatively ranked footprint results that differ in comparative performance rank and to sensitivity analysis results.

5.3 Methods

5.3.1 Data

Data in this study originates from the Langhill herd of Holstein Friesian cows which form one of the world’s longest running genetic line × feeding systems experiments (Pollott and Coffey, 2008). Data was used from all cows belonging to the herds based at the SRUC’s Crichton Royal Farm, Dumfries, Scotland between 2006 to 2010 and from 2012 to 2015. A Select (S) group of cows sired by bulls with high predicted transmitting abilities (PTA) for fat plus protein yield are compared with a Control (C) group sired from UK average merit bulls (Pryce et al., 2001). System trials were managed according to the same rules and each regime was designed to allow animals to express their potential for milk production, within the limitations based them from the feed rations offered. Trial cows were milked three times per day, housed in the same building, with cubicles, and concrete passageways that were cleared with automatic scrapers. A complete diet was offered as a total mixed ration (TMR), irrespective of milk yield and stage of lactation. Sub-groups alternated every 3 days between being fed through Hoko gates (Insentec BV, Marknesse, The Netherlands), which recorded individual feed intake, or being fed as one group behind a strap.

The four dietary treatments compared in this analysis were;

i) a high forage (HF) composite system which can be defined as a regime for grazing cows when availability of grass is adequate and housed during inclement winter months when animals are fed conserved forage and concentrate through a total mixed ration (TMR)

ii) a home grown (HG) partially housed system; defined here as a regime where all feed is grown on the farm using legume based protein sources with no purchased feeds except minerals, and where animals are housed for one period each day and fed a conserved forage TMR

iii) a low forage (LF) housed system has animals confined all year round being fed a ration of conserved forage and concentrate through a TMR

iv) a novel by-product (BP) fully housed system feeding mainly non-human edible by-products or co-products from the food industry with no forages.

Forage components of the complete diet for the LF system consisted of home-grown grass silage, maize silage and whole crop wheat alkalage, however, within the BP system only non-human edible concentrates and straw were consumed (Table 5.1). TMR’s were sampled monthly and analysed for metabolisable energy (ME) content, dry matter (DM), digestibility and crude protein (CP) content of the ration. LF and HF cows were fed 0.75 kg/day fresh weight of a standard concentrate whilst in the milking parlour. Intakes of grass were not measured however periods of time spent grazing were recorded and samples of fresh grass were taken and analysed. Cows were dried off eight weeks prior to estimated calving date and consumed a straw based diet and after four weeks were fed a transition diet which consisted of 30% of the average daily dry matter intake of the appropriate milking cow ration. Youngstock were managed as one group, with rations attributed by age, for bull and heifer calves 0-12 months, and for heifers from 12 – 36 months.

Table 5-1 Ration constituent proportions in fresh weight and dry weight

Diet	Component	Fresh Weight (kg/day)	Dry Weight (kg/day)	Fresh Weight Proportion
Low Forage	Wheat Grain	4.3	3.83	0.096
	Sugar Beet Pulp Molasses	3.5	3.14	0.078
	Soya Bean Meal	3.1	2.81	0.068
	Distillers Grains (Wheat)	1.5	1.34	0.033
	Soya Hulls	0.6	0.57	0.014
	Protected Fat Megalac	0.3	0.33	0.008
	Sopralin & Alkcarb	0.4	0.3	0.009
	Grass Silage	19.8	6.6	0.436
	Maize Silage	8.2	2.2	0.181
	Alkalage	3.3	2.2	0.073
	Minerals/Vitamins	0.25	0.25	0.006
	Total	45.4	23.6	
By-product	Barley Straw	6.5	5.30	0.200
	Sugar beet pulp molasses	5.5	4.90	0.169
	Breakfast Cereal	3.3	3.00	0.102
	Distillers Grain	8.0	2.20	0.246
	Biscuit Meal	2.2	2.00	0.068
	Wheat Distillers Dark Grains	2.2	2.00	0.068
	Soya Bean Meal	2.2	2.00	0.068
	Molasses Cane	2.0	1.30	0.062
	Minerals (High P)	0.2	0.20	0.006
	Protected Fat	0.4	0.38	0.012
	Total	32.5	23.3	
High Forage	Grass Silage	17.5	9.6	0.426
	Maize Silage	12.9	3.2	0.314
	Alkalage	4.9	3.2	0.119
	Rapeseed Meal	1.7	1.5	0.041
	Barley Distillers Grains	2.5	2.3	0.061
	Wheat Distillers Grains	1.4	1.2	0.034
	Minerals/Vitamins	0.2	0.2	0.005
	Total	41.1	21.2	
Homegrown (Winter Ration)	Grass Silage	35.1	9.0	0.587
	Spring Beans	5.5	4.7	0.092
	Wheat Grain	4.0	3.4	0.067
	Red Clover Silage	10.0	2.0	0.167
	Maize Silage	4.0	1.0	0.067
	Lucerne silage	2.0	0.6	0.017
	Minerals/Vitamins	0.2	0.2	0.003
	Total	60.8	20.9	

Four dietary treatments and two genetic lines of cow allowed a comparison of eight diverse dairy production systems. Herds were managed in feed groups which contained cows of both genetic lines and animals remained in the same system for 3 lactations or until there was a suitable replacement. Cows were milked thrice per day and each herd calved all year round (AYR). Milk yield was measured at each milking with a sample taken once a week and analysed for fat and protein constituents. Liveweights were recorded three times per day after milking.

5.3.2 Data Analysis - LCA

The goal and scope of a study help define system boundaries, appropriate functional units, methods and approach to allocation of co-products, and impact categories of interest. Boundaries applied in this study were ‘cradle to farm gate’ which included all stages of production from acquisition of farm inputs and raw materials until the milk or animals left the farm. This boundary included input emissions generated off farm, such as those associated with purchased feeds, transport, fertiliser production and electricity production. On farm inputs included applications of fertilisers, sprays, fuel, crops and field activities, animal feed, livestock of all ages and the management of their manure. Not included in this study were indirect emissions such as staff travel, maintenance of farm buildings, disposal of dead animals and ancillary purchases such as medicine and disinfectants used to clean infrastructure. Carbon sequestration of farm woodland by age and type is included and reported separately as a reduction of net emissions. Standard functional units related to dairy LCA’s of fat and protein corrected milk (FPCM) was applied using the following equation (IDF, 2010):

$$\text{FPCM} = \text{Production (kg/year)} \times [0.1226 \times \text{Fat (\%)} + 0.0776 \times \text{Protein (\%)} + 0.2534]$$

Allocation describes how GHGs are attributed to the products, and possible co-products that leave the farm and the methods applied can affect the estimation of emissions (Cederberg and Stadig, 2003). In this case, as no crops were sold, co-products included animals culled and manure exported from the system. Methods of allocation available in LCA studies include biological causality, system expansion, economic allocation, mass allocation and no allocation (Audsley et al., 1997). System expansion is a method of substitution that considers how co-products could be a replacement for other products in the global economy, for example in dairy production a manure co-product could replace purchased fertiliser. Economic and mass allocation methods divide the impact by how much the products cost or weigh.

Studies of EU milk production apply an allocation to milk of 85% whereas, biological causality assigns only emissions from lactating cows to milk production and this excludes young stock and dry cows (Cederberg and Mattsson, 2000; O'Brien et al., 2010). Allocation of co-products leaving the farm by mass of milk and meat is recommended by the International Dairy Federation (IDF), with a default value of 85.6% (IDF, 2010). The AgRECalc model applies the IDF (2010) method of allocation by mass of milk and animal weight because UK milk price has been historically volatile, and management of dry cows would be argued to form an integral part of UK dairy systems. Fluctuating milk prices could produce extreme results that are not comparable with other studies.

Table 5-2 Average annual dairy system production characteristics for Select merit cows

	Low Forage		By-product		High Forage		Home Grown	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Herd size	45	3.5	50	2.1	51	3.8	55	2.2
Weight, kg/cow	647	11.4	663	21.7	626	8.6	651	33.3
DMI, kg/cow/day	19.0	3.93	22.1	4.42	17.3	3.72	17.2	3.31
Yield, kg/cow/day	35.6	1.36	34.6	1.41	26.8	0.82	24.6	0.67
Butterfat, %	3.9	0.74	3.5	0.25	4.0	0.06	3.9	0.31
Protein, %	3.3	0.40	3.2	0.07	3.3	0.05	3.4	0.07

DMI = Dry matter intake, sd = standard deviation

The impact category focus is climate change and is assessed by measuring total GHG emissions expressed in kg CO_2e, stemming from annual inventories of the dairy systems. A life cycle inventory of data from system years 2006-2010 for HF and LF and system years 2012-2015 for HG and BP treatments. Dairy system inputs and outputs were determined annually using data extracted directly from the database and an array of production indicators are presented in Table 5.2 for Select and Table 5.3 for Control systems. Emissions from livestock were calculated using monthly herd dynamic data that was prepared for each of the systems for all years to determine livestock within each of the age categories, those culled, died, or sold, as well as dry and transition cows.

Table 5-3 Average annual dairy system production characteristics for Control merit cows

	Low Forage		By-product		High Forage		Home Grown	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Herd size	50	0.6	52	1.8	54	1.0	55	2.4
Weight, kg/cow	625	11.3	632	5.8	599	12.0	611	18.5
DMI, kg/cow/day	18.1	4.02	20.3	5.53	16.35	1.16	15.52	2.28
Yield, kg/cow/day	31.1	1.54	28.8	1.55	24.1	0.83	22.8	0.61
Butterfat, %	3.6	0.13	3.3	0.17	3.8	0.07	3.6	0.25
Protein, %	3.1	0.06	3.0	0.04	3.2	0.03	3.2	0.1

DMI = Dry matter intake, sd = standard deviation

Land required annually for those systems consuming crops grown on the farm was determined from amounts of each crop component fed to the herds and the DM content of the crop when fed. Dry matter losses occurred at harvest, during ensiling or baling with estimated losses from grass silage, wheat alkalage, red clover bales and maize silage applied when considering land requirements for each system. This was as the crops were not grown or ensiled separately for each of the dairy systems (Bastiman and Altman, 1985; Xiccato et al., 1994). Total land required for each system year was calculated by adding on-farm land to an estimate of off-farm land. Off farm land was estimated using economic allocation of feed components within each of the diets, using national data for wheat SAC (2016) and Feedprint (Vallinga et al., 2013) for processed feeds, these are shown in Table 5.4 with their GHG emission factors.

Table 5-4 GHG emission and land use factors applied to dairy system purchased feed components

Diet	Component	Economic g CO_2 e /kg	Mass g CO_2 e /kg	Land use m^2/kg
Low Forage	Wheat Grain	434	349	1.43[a]
	Sugar Beet Pulp Molasses	120	245	0.22
	Soya Bean Meal	575	750	2.42
	Distillers Grains (Wheat)	285	5795	0.98[a]
	Soya Hulls	333	754	0.33
	Protected Fat	501	2941	0.33
By-product	Barley Straw	196	306	0.61
	Sugar beet pulp molasses	120	245	0.22
	Breakfast Cereal	296	1015	1.11
	Distillers Grains (Wheat)	285	5428	0.98[a]
	Biscuit Meal	118	126	1.25
	Wheat Distillers Dark Grains	285	5795	0.98[a]
	Soya Bean Meal	575	750	2.42
	Molasses Cane	262	681	0.15
	Minerals	180	180	0.33
	Protected Fat	501	2941	0.33
High Forage	Rapeseed Meal	529	1221	1.50
	Barley Distillers Grains	285	5795	1.15[a]
	Wheat Distillers Grains	285	5795	0.98[a]

EF= Emission factor, Source unless otherwise stated: Feedprint (Vallinga et al., 2013), [a] (SAC, 2016)

Maize, wheat, and spring beans were sown annually, lucerne every two years and grassland for pasture and silage every 5 years. Up to three cuts of grass silage were harvested each year and any instances of double cropping of fields were noted with the lengths of time attributed to each crop allocated accordingly. For example, a field to be sown for maize may have been cut for silage before ploughing and there were instances where a grass silage cut was taken from a field sown for red clover bales. Applications of nitrogen (N), phosphorus (P), and potassium (K) fertilisers and organic fertiliser were determined by the farm manger using a long-term nutrient management plan and recorded for each crop type with application rate and fertiliser type. Sprays of insecticides, fungicides and herbicides, were included from the database, where available, along with information obtained directly from the supplier (pers. comm. Richard Bray). Organic fertiliser was applied as solid manure or as liquid slurry using a splash plate, trailing shoe, or by shallow injection. Manure management emissions for each of the systems were allocated by the length of time the cows spent at either liquid storage, solid storage or depositing at pasture. Liquid slurry stems from the housed milking cows, however, the proportions of time spent grazing were determined and used to allocate deposition directly at pasture. Dry, transition cows and young stock generated solid manure. Manure generated by the dairy systems that was not applied to the crops was exported.

Use of petrol and diesel, including the fuel needs of contractors, for each required activity was recorded in the database and then attributed to a feeding system by task, such as fertiliser application, and then by genetic group. Activities on the farm that required fuel related to crop management included fertiliser applications and herd management, such as feeding. Electricity use (kWh) was estimated from milk yield (Sheane et al., 2010) as power consumed was not recorded separately for each of the systems. Annual diet digestibility and CP for each of the systems were determined from proportional intakes from monthly TMR and feed component sample analysis. Non crop areas such as woodland and biodiversity strips were apportioned using annual IACS data (Pers. comm Hugh McClymont, SRUC) depending on the age and type of woodland. Outputs of milk were summed for the systems annually and weekly fat and protein constituents were averaged.

5.3.3 Inventory

An inventory was prepared for each of the eight systems which provided annual inputs and outputs for 36 years in total for subsequent analysis using SRUC's AgRECalc v1.4 (SRUC, 2014) a foot-printing and resource efficiency tool which utilises IPCC methodology (Dong et al., 2006). A PAS2050 (BSI, 2011) accredited version is available online and the tool is used by both farmers and livestock researchers (Toma et al., 2013; Sykes et al., 2017). Tier II emission factors (EF's) were applied for livestock and manure management and Tier I for fertiliser and crop residue N_2O (Dong et al., 2006). Livestock emissions from dairy cows included those stemming from manure and enteric CH_4, direct and indirect N_2O from manure management and additionally leaching and ammonia (NH_3) volatilisation arising from the application and deposition of manure as well as indirect CO_2 from purchased feeds. Amounts of N excreted were estimated from N consumed less N utilised for production, growth and maintenance, which were derived from dry matter intake and CP content of the diets. Land category emissions arise from manure and fertiliser application and include N_2O from applications to soil, volatilisation, leaching and run-off as well as N_2O emissions from crop residues. Embedded emissions from fertiliser included those associated with manufacture and distribution, which, in the case of the Haber process for N, can be energy intensive. A description of the categories of emission factors and equations applied within the model are shown in Table 5.5.

Table 5-5 Selected emission factors and calculations applied within the model with source

Category	Emission	Measure	Factor	Source
Land	Crop residues, manure and N (fraction of emissions to soil)	Direct N_2O	0.01	IPCC 2006 Ch11 11.11
	Crop residue losses leaching	Indirect N_2O	30%	IPCC 2006 Ch11 11.24
Livestock	Manure per cow	Max CH_4/kg VS	$0.24m^3$	IPCC 2006 Ch10 10.44
	N excretion	kg N/1000 kg cow /day	0.48	IPCC 2006 Ch10 10.59
	Enteric fermentation (CH_4 conversion)	% of gross feed energy	6.5%	IPCC 2006 Ch10 10.30
Embedded	Fertiliser N	kg CO_2e	7.11	CT Footprint Expert 3.1
	Fertiliser P	kg CO_2e	1.85	CT Footprint Expert 3.1
	Fertiliser K	kg CO_2e	1.76	CT Footprint Expert 3.1
	Herbicides	kg CO_2e /kg ai	29.5	Audsley et al., 2009
	Insecticides	kg CO_2e /kg ai	28.5	Audsley et al., 2009
	Fungicides	kg CO_2e /kg ai	37.6	Audsley et al., 2009
Energy	Diesel	kg CO_2e	3.17	DEFRA/DECC 2015
	Petrol	kg CO_2e	2.66	DEFRA/DECC 2015
	Electricity	kg CO_2e	0.48	DEFRA/DECC 2015
Sequestration	Broadleaf Woodland >20 yrs	C fraction DM growth	0.48	

VS=Volatile solids, DM= Dry matter

GHG emissions from production, processing, and distribution, embedded in purchased feeds brought onto the farm, were calculated from EF's associated with each feed component within the TMR's of the four diets. The LF and HF diets included a proportion of distillery products and the BP system included purchased by-products from the bakery, distillery, brewing and confectionary industries. Emissions from co-product feeds were allocated proportionally by component, for example, rapeseed, 40% oil, 60% meal (Cederberg and Mattsson, 2000). Emission factors attributed to feeds purchased for the LF, HF and BP systems followed an economic allocation method by feed component in the first instance and a mass allocation method as a comparison. Leguminous by-products, soya bean meal and soya hulls were included in the LF and BP housed system TMR's at proportions of 14% and 9% respectively. Legumes grown on the farm for the HG system represented 25% of the winter TMR and there were no legumes or leguminous by-product components fed within the HF regime (Table 5.1).

5.3.4 Statistical analysis

Statistical analyses were carried out in R version 3.5.2 (R Core Team, 2019) using lme4, car, and lattice packages to determine the effect of dairy production system upon product GHG emissions calculated using economic allocation (Bates et al., 2015; Sarkar, 2008). A linear mixed model was fitted and included fixed effects of feeding regime, genetic merit, and a random effect of year. A one-way ANOVA, and Tukey pairwise comparison test was carried out to determine significance of the production systems using the following model:

$$Y_{ijk} = \mu + F_i + M_j + T_k + F_i M_j + \varepsilon_{ijk}$$

Where, y_{ijk} is the impact of GHG emissions using economic allocation and expressed per kg FPCM

$\mu = grand\ mean$

$F_i = feed\ type\ (i = 1\ to\ 4) \quad fixed\ effect$

$M_j = genetic\ merit\ (j = 1\ to\ 2) \quad fixed\ effect$

$T_k = year\ (k = 1\ to\ 9) \quad random\ effect$

$\varepsilon_{ijk} = residual\ error$

5.3.5 Sensitivity analysis

Stochastic simulations were carried out using Model Risk (Vose Software) to assess the effect of annual variation in neutral cellulase gammanase digestibility (NCGD) and CP content of the rations on dairy system GHG emissions. Baseline carbon footprints, determined using economic allocation of feeds, were estimated by AgRECalc (SRUC, 2014). Monte Carlo analysis using repeated random sampling was used to generate distributions of footprints for the dairy systems that accounted for uncertainty stemming from variability in NCGD and CP content for each treatment group. Descriptive statistics for the NCGD and CP distributions are shown in Table 5.6. Exponential and Log Laplace distributions were fitted to NCGD and CP analysis results respectively, and Monte Carlo simulations with 10,000 iterations (seed = 2605) were carried out.

Table 5-6 Diet digestibility and crude protein content, mean sd, and range

	NCGD (g kg DM^{-1})			Crude Protein (g kg DM^{-1})		
	Mean	sd	Range	Mean	sd	Range
Low Forage	83.9	4.32	12.8	18.0	0.97	2.5
By-product	74.9	2.83	6.0	20.3	0.27	0.8
High Forage	72.8	2.64	8.5	17.1	0.44	1.1
Home Grown	75.0	3.04	6.7	18.1	1.62	3.9

sd = Standard deviation, NCGD= Neutral cellulase gammanase digestibility

5.4 Results

5.4.1 Effect of allocation method

The average annual carbon footprint for milk produced in each of the dairy systems was calculated using both economic and mass allocation of feed components, which resulted in large differences in the ranking of the different systems (Figure 5.1). In the housed systems, with economic allocation, the BP diet attracted greater emissions per kg product at 1.07 kg compared CO_2e / kg FPCM compared with the LF system, which averaged 0.95 kg CO_{2e}. The BP ration was formulated from mainly non-human edible food and drink industry co-products and the TMR produced only marginally less GHGs than the LF diet. With the economic allocation ration EF’s per tonne in the LF diet was 256 kg CO_2e and 249 kg CO_2e in the BP diet. Milk quality in the BP diet was, on average, lower in fat and protein content in comparison with the LF system.

Economic allocation of feed components in the HF and HG grazed system footprints led to similar product emissions per kg of FPCM at 1.15 and 1.16 kg CO_2, respectively, this was as a result of lower embedded emissions in the HG system that were outweighed by higher emissions from energy and fuels (Figure 5.1). The HG system attracted higher fuel use associated with greater crop production. Economic allocation of EF's for the HF and HG TMR's were 206 kg and 252 kg of CO_2, respectively.

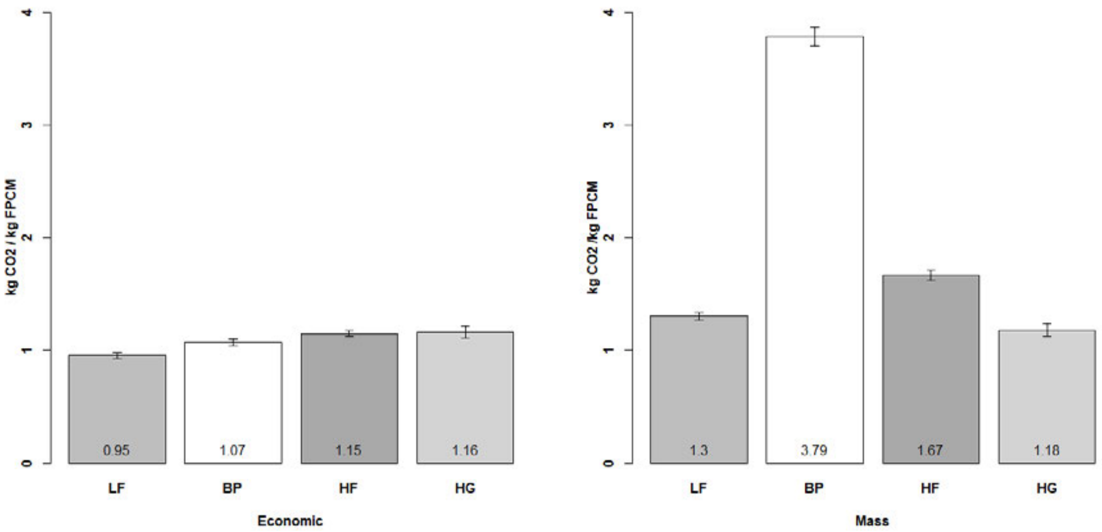


Figure 5.1 Select merit dairy system average annual footprints per kg of FPCM using Economic and Mass allocation of feed components.

LF= Low Forage, BP=By-product, HF= High Forage, HG =Home Grown

Mass allocation of feed components led to increases in system footprints per kg milk because emissions were higher for all diet TMR's with the exception of HG at 473, 2072, 757 and 252 kg CO_{2e} / tonne, for the LF, BP, HF and HG systems respectively. Ration EF's increased using mass allocation because feed components such as industry by-products tend to attract higher emissions when additional processing into animal feed is required. On average, in the housed systems, BP diet emissions trebled per kg product at 3.79 kg CO_{2e} / kg FPCM, while the LF system product emissions averaged 1.3 kg CO_{2e} / kg FPCM (Figure 5.1). Purchased concentrates, and food and drink industry co-products such as brewers grains attract greater mass allocation emissions, however, farm grown crop emissions were generally similar irrespective of allocation method, with the exception of wheat grain (Table 5.4). In the grazed HF system mass allocation of feed components increased product footprints because distillers' grains and rapeseed meal elevated emissions. The HG grazed system footprints were least effected by allocation method as purchased feed was limited to minerals and diet component EF's were all equivalent apart from wheat grain.

Table 5-7 Analysis of variance (ANOVA) results showing dairy system GHGs by emission type using economic allocation

Variable	Level	Land CO$_2$e	Livestock CO$_2$e	Embedded CO$_2$e	Energy CO$_2$	Sequestered CO$_2$	Total CO$_2$e
System	LFS	0.06^{a}	0.49^{a}	0.34^{a}	0.08	-0.01^{a}	0.96^{a}
	BPS	0.00	0.61^{b}	0.39^{b}	0.07	0.00	1.07^{b}
	HFS	0.09^{b}	0.73	0.28^{c}	0.08	-0.03^{b}	1.15^{c}
	HGS	0.11^{c}	0.73	0.22^{d}	0.15^{a}	-0.05^{c}	1.16^{c}
	LFC	0.07^{d}	0.59^{c}	0.40^{e}	0.09	-0.02^{d}	1.13^{d}
	BPC	0.00	0.71^{d}	0.46^{f}	0.07^{b}	0.00	1.24^{e}
	HFC	0.10^{e}	0.84^{e}	0.33^{g}	0.08	-0.03^{e}	1.33^{f}
	HGC	0.12^{f}	0.81^{f}	0.25^{h}	0.16^{c}	-0.06^{f}	1.28^{e}
Diet	LF	0.06^{a}	0.54^{a}	0.37^{a}	0.08^{a}	-0.02^{a}	1.04^{a}
	BP	0.00	0.66^{b}	0.43^{b}	0.07^{a}	0.00	1.16^{b}
	HF	0.09^{b}	0.79^{c}	0.31^{c}	0.08^{a}	-0.03^{b}	1.24^{c}
	HG	0.11^{c}	0.77^{d}	0.23^{d}	0.16^{b}	-0.05^{c}	1.22^{c}
Genetics	Control	0.07	0.74^{a}	0.36^{a}	0.10	-0.03	1.24^{a}
	Select	0.06	0.64^{b}	0.31^{b}	0.09	-0.02	1.08^{b}
R^2		0.97	0.71	0.79	0.92	0.97	0.87

Results showing least square means (lsm), different superscripts within a column denote significant differences between levels of the same variables ($p < 0.05$). LF= Low Forage, BP=By-product, HF= High Forage, HG =Home Grown, S=Select, C=Control

5.4.2 Statistical analysis

A one-way ANOVA was conducted to compare GHGs from the four feeding regimes and two genetic lines using an economic allocation of feed emissions and results (Table 5.7). Normality checks and Levene's test were carried out and the assumptions were met. The effect of the interaction was significant ($p <0.01$) and there was a significant difference in mean GHGs per kg FPCM between the feed groups [$F(3,28)= 15.6$, $p < 0.001$] and the genetic merit [$F(1,28)= 46.5$, $p < 0.001$]. Post hoc comparisons using the Tukey test showed mean Select and Control merit GHG totals to be significantly different ($p < 0.05$) in LF, BP and HF feed types but not significantly different in the HG diet. Tukey test results showed that the LF diet was significantly different from BP ($p<0.05$), the HF and the HG ($p<0.001$) diets for GHG totals. Significant differences in mean embedded emissions were found between all management systems ($p<0.05$) and livestock emissions were all significantly different ($p<0.05$) apart from HFS and HGS regimes (Table 5.5).

5.4.3 Sensitivity analysis

Simulated footprints were generated using economic allocation of feeds to obtain distributions of dairy management system results if variation in NCGD and CP levels were considered. Footprint simulations considering the effect of NCGD and CP variation differed significantly from system footprints using standard methods ($p< 0.001$). Mean milk footprints were increased in the BP and HF systems and decreased in the LF and HG systems, in comparison with methods which apply an average annual figure for digestibility and CP. Accounting for nutritional variation of the rations throughout the year had widened footprint ranges, and altered comparative dairy system performance ranking. For Select merit cows in the housed systems, the BP regime produced greater emissions per kg FPCM, at 1.21 kg CO_2, however, in the grazed systems the HG had lower emissions compared with an economic allocation, at 1.15 kg CO_2 (Figure 5.2). Higher average diet digestibility combined with a lower average CP content in the LF system led to lower mean emissions, in comparison with the other dairy systems and allocation methods. High production Select merit cows managed in production systems with greater proportions of farm grown forage in the diet, such as the HG system, generally attracted wider ranges of potential GHG emissions (Figure 5.2). Control merit cows within the LF system led to lower emissions on average.

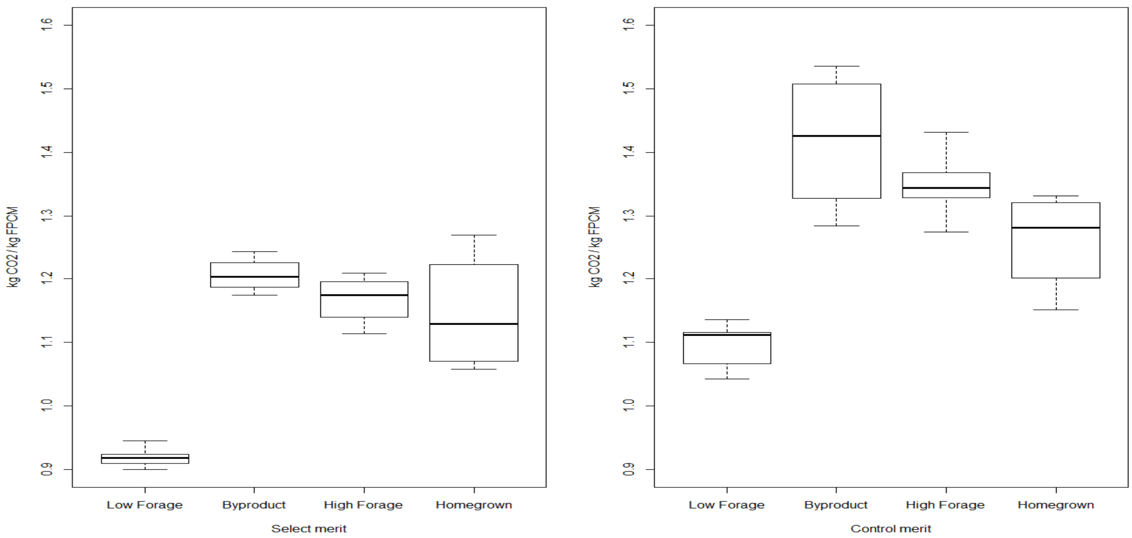


Figure 5.2 Boxplots for Select and Control merit showing economic allocation dairy system emissions with effect of NCGD and CP variation in the ration

CP= Crude protein, NCGD= Neutral cellulase gammanase digestibility

Sources of GHGs within the carbon footprints varied by dairy management regime, therefore farm mitigation strategies may prove more effective if applied by system type. Land and crop GHG emissions stem from crop residues, manure and fertiliser application and these ranged from zero in the BP system to 0.11 kg CO_{2e} in the HG system (Figure 5.3). Embedded emissions are generated by energy consumed in the manufacture of feeds, fertilisers, and pesticides and also in the use of bedding. Embedded emissions were greatest in the BP housed system, at 0.46 kg CO_2e /kg FPCM, because all feed and bedding were imported, and the HG grazed system attracted higher embedded N fertiliser emissions than the HF system, as a larger area of on farm crop land replaced purchased feeds. (Figure 5.3).

Livestock emissions that arise from enteric fermentation and manure management were greater in the HF and BP systems, at 0.79 and 0.68 kg CO_2e / kg FPCM, compared with 0.57 and 0.66 kg CO_2e / kg FPCM in the LF and HG systems, respectively (Figure 5.3). Higher emissions arose from greater amounts of manure stored in the BP system and from depositions while at pasture in the HF system. Emissions related to energy use were greater in the HG system, as this stemmed from fuel used for crop related activities. Sequestered carbon estimated to occur within the woodland in the LF, HF and HG systems, lowered Select merit footprints by 0.01, 0.03, and 0.05 kg CO_2e / kg FPCM, respectively (Table 5.7).

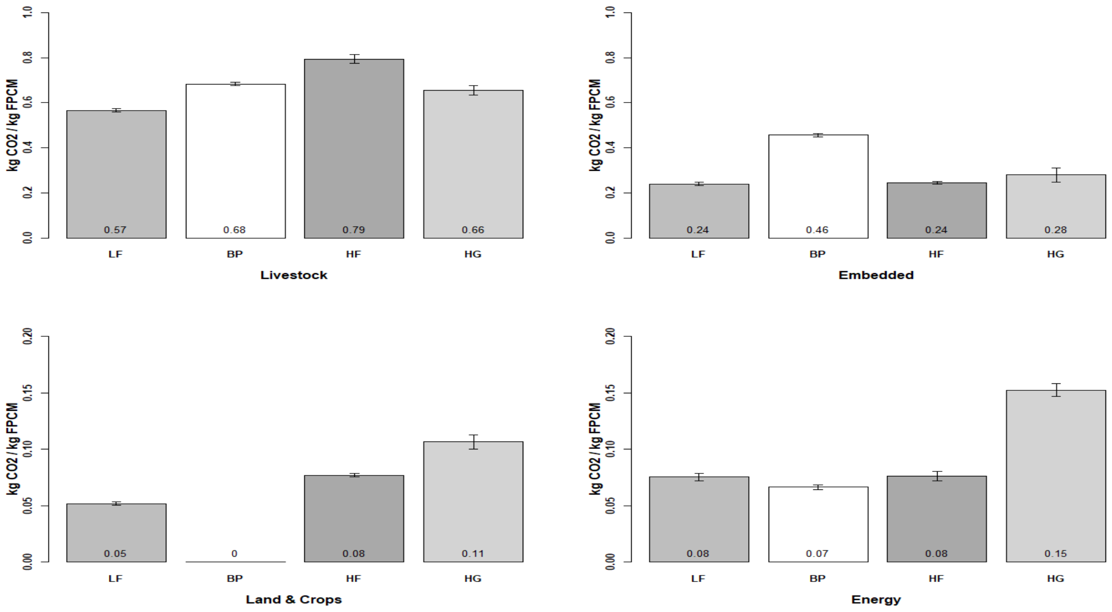


Figure 5.3 Dairy system GHGs by emission source type with standard error considering NGCD not including C sequestration

5.4.4 Effect of increased legume forages

The HF system ration included feeds requiring crop rotations of grass silage, maize and wheat, which required N fertilisers and were ensiled on farm. Crop products were combined with purchased concentrates and on average the HF diet consisted of 75% forage on a DM basis and 1.3 tonnes of concentrate per cow (March et al., 2017). In comparison with the HF diet, the HG ration required less maize crop, as the purchased distillers' grains and rapeseed meal were replaced with farm grown proteins, such as, spring beans and lucerne. The HG herds were grazed for an average of 26% of the year, whereas the HF cows were grazed for an average of 30% and attracted greater emissions from deposition at pasture. For Select merit cows, however, feed intakes on a DM basis were similar in HF and HG systems (Table 5.2). Average milk yield reduced slightly, by 98 kg per cow from 7,575 kg in the HFS system to 7,477 kg in the HGS system, although, milk quality was similar in both the systems (Table 5.2).

Economic allocation of feed components generated similar average product emissions for HF and HG systems at 1.15 kg and 1.16 kg, respectively. Mass allocation increased the HF milk footprint to 1.67 kg CO_2e /kg due to the proportion of distillers' grains in the ration. Accounting for nutritional variation slightly reduced the HG average to 1.15 kg CO_2e per kg FPCM and increased the HF to 1.17 kg CO_2e per kg FPCM. If C sequestration was not included, the footprints would, on average, be equivalent at 1.19 kg CO_2e per kg FPCM. Trade-offs between livestock manure emissions and energy use to grow crops has led to similar milk total emissions being returned from the HG and HF systems (Table 5.7). Total 'on farm' land use per milking cow increased from an average of 0.86 ha to 1.23 ha when comparing the HF and HG systems. The HG system attracted greater embedded emissions than the HF system, these stemmed from the use of fungicide and herbicide applications to the wheat and spring beans.

Table 5-8 Dairy system GHG emissions (kg CO_2e / kg FPCM) by category using economic allocation of feeds and considering nutritional variation of both CP and NCGD

	Land		Livestock		Embedded		Energy		Sequest’n		Total	
	mean	sd	mean	sd	mean	sd	mean	sd	Mean	sd	mean	sd
LFS	0.05	0.003	0.57	0.013	0.24	0.014	0.08	0.007	-0.01	0.002	0.92	0.04
BPS	0.00	0.000	0.68	0.014	0.46	0.016	0.07	0.004	0.00	0.000	1.21	0.03
HFS	0.08	0.003	0.79	0.036	0.24	0.013	0.08	0.007	-0.03	0.002	1.17	0.06
HGS	0.11	0.011	0.66	0.036	0.28	0.055	0.15	0.010	-0.05	0.003	1.15	0.11
LFC	0.06	0.006	0.68	0.020	0.29	0.009	0.09	0.012	-0.02	0.001	1.09	0.05
BPC	0.00	0.000	0.80	0.051	0.55	0.045	0.07	0.005	0.00	0.000	1.42	0.10
HFC	0.09	0.008	0.91	0.028	0.30	0.020	0.08	0.013	-0.03	0.002	1.35	0.07
HGC	0.11	0.012	0.73	0.051	0.32	0.028	0.16	0.008	-0.06	0.003	1.26	0.10

S=Select merit, C=Control merit, sd = Standard deviation,

CP = Crude Protein, NCGD= Neutral cellulase gammanase digestibility

5.4.5 Effect of genetic merit

Control merit cows total product footprints across each of the management regimes were significantly higher ($p<0.001$) in comparison with high production Select merit cows, on average by 15% (Table 5.7). Livestock and embedded emissions were also significantly higher from control merit ($p<0.01$). On average, across each of the management regimes, Control merit cows yielded less milk volume and milk constituents when compared to Select merit animals. System ranking for Control merit was equivalent to Select ranking for footprints encompassing nutritional variation (Figure 5.2). Control merit carbon footprints were higher than Select merit apart from in the LF system, where the Control merit resulted in slightly lower emissions than Select merit in the BP, HG and HF management. The housed LF regime incurred fewer GHGs per litre of FPCM than the BP system irrespective of merit and footprinting methodology, mainly because of emissions embedded in the production of feeds. A Control merit cow within the BP system attracted greater product emissions than other systems and merit at 1.42 kg CO_2e / kg FPCM.

Table 5-9 Select merit dairy system land use (ha) on and off farm (mean and standard deviation)

Dairy system	On-farm Land		Off-farm land		Total land
	mean	sd	mean	sd	mean
Low Forage	29.4	4.99	45.1	2.23	74.5
By-product	0.60	0.0	58.9	4.07	59.5
High Forage	41.6	8.23	21.8	2.53	63.4
Home Grown	67.6	2.82	11.2	2.18	78.8

5.4.6 Effect of land use as a functional unit

On average, land requirements on and off farm for Select merit cows (Table 5.9) showed the BP system required the least amount of land in total, due to the high proportion of human inedible crop products and industry co-products. Land as a functional unit showed the HG system as least GHG intensive, when output of product is included with total land, as the BP dairy system emits fewer GHG per hectare (Table 5.10).

Table 5-10 Dairy system mean GHG emissions (kg CO_2e) per functional unit

Unit	Method	Merit	Low Forage	By-product	High Forage	Home Grown
kg FPCM	Economic Allocation	Select	0.95	1.07	1.15	1.16
FPCM	Mass Allocation	Select	1.30	3.79	1.67	1.18
ha	Economic Allocation	Select	6,939	9,512	8,164	6,309
FPCM / ha	Economic Allocation	Select	71.1	63.9	72.8	91.7
FPCM	NCGD & CP Sensitivity	Select	0.92	1.21	1.17	1.15
FPCM	NCGD & CP Sensitivity	Control	1.09	1.42	1.35	1.26

5.5 Discussion

Using an LCA approach, this study demonstrates the importance of allocation method used to attribute GHG emissions of animal feeds and, in addition, the effect of nutritional variation on the perceived performance of novel and conventional UK dairy systems. Results show that ranked performance of the dairy management types alter depending on the approach used to calculate impact and whether uncertainty is included (Table 5.11). Economic allocation resulted in mean dairy system emissions that ranged from 0.95 to 1.16 kg CO_{2e} / kg FPCM but were lower than the UK average of 1.25 kg CO_2e (AHDB, 2014). Footprints were, on average, higher using mass allocation EF's, whereas, accounting for uncertainty stemming from changes in diet CP and digestibility altered the dairy system ranking. Mass allocation of feed component emissions raised product emissions on average by 41%, for the more conventional LF and HF rations, which comprised of a mixture of grown crops and purchased concentrates.

Novel rations such as those used in the BP system required less land, however incorporating high percentages of co-product based animal feeds can lead to greater GHG emissions as a consequence of upstream processing, such as drying or milling, which can be energy intensive (Vellinga et al., 2013). Ruminant diets for high yielding cows can be formulated to achieve lower emissions, and to make more efficient use of human inedible co-products (Wilkinson and Garnsworthy, 2017), however, not all co-product feeds are low carbon and feeding TMR's all year round usually requires cows to be housed in adequate modern animal housing facilities with slurry storage systems.

In Scotland, industry co-products have traditionally been used as animal feeds, however, feeds such as distillers' grains contain added water which stems from the mashing stage of the whisky making process. This hugely inflates mass balance emissions and drying grains requires a substantial input of energy as the water content has to be reduced from approx. 75% to under 10%. Product quality in the BP system was also reduced, this was reflected through lower milk fat and protein which would have financial consequences for farm income. Financial analysis of the LF and HF regimes found a Control merit cow in a housed regime to be least profitable because milk yields were not sufficiently high to justify the feed costs (March at el., 2017).

Table 5-11 Ranked dairy system mean total GHG emissions (kg CO_2e)

Method	Unit	Merit	LF	BP	HF	HG
Economic Allocation	FPCM	Select	1	2	3	4
Mass Allocation	FPCM	Select	2	4	3	1
Economic Allocation	ha	Select	2	4	3	1
Economic Allocation	FPCM / ha	Select	2	1	3	4
NCGD & CP Sensitivity	FPCM	Select	1	3	4	2
NCGD & CP Sensitivity	FPCM	Control	1	3	4	2

Statistical analysis showed that, on average across all diets, product emissions from Control merit cows using an economic allocation were 15% higher and therefore improving genetic merit offers an immediate emissions reduction strategy, mainly through increased milk yields. In addition, GHG emissions can be reduced by selecting for feed efficiency (Bell et al., 2011) and this could be accelerated using techniques such as genomics in the herd to enhance overall feed efficiency and *in vitro* fertilisation (Hailu, 2018; Pryce and Bell, 2017; Gifford and Gifford, 2013). Considering the diets, the total emissions differed significantly ($p<0.05$), apart from the HF and HG rations, however the emission types did differ significantly between these systems. This highlights that for dairy systems mitigation potentials and measures implemented, should be quantified and designed by first considering the production method and the emission source.

Carbon footprints from livestock systems are complex and intricate, and product GHG emission intensity totals do not always illuminate system specific mitigation pathways. Current methods of carbon auditing should be improved by accounting for uncertainty and effectively communicating that uncertainty within the calculated livestock footprints (Zehetmeier et al., 2014; Milne et al., 2015). Monte Carlo simulations can generate multiple footprints to form probability distributions that provide increased confidence in results when establishing mitigation pathways to alleviate impacts. Sensitivity analysis provides a deeper technical understanding of complex systems and is recommended to clarify potential impacts (Baldini et al., 2017). Accounting for epistemic uncertainty arising from manure CH_4 and N_2O and enteric CH_4 emissions has shown to inflate GHG emissions in livestock footprints (Sykes et al., 2019). Emissions of N_2O from manure and enteric CH_4 were found to generate most variation in dairy footprints and the N_2O mainly stemmed from the IPCC emission factor for volatilisation and atmospheric deposition of N (Ross et al., 2017). Studies quantifying uncertainty and assessing sensitivity of milk production LCA’s have also investigated management changes, C sequestration, manure storage and changes in energy consumption (O’Brien et al., 2012; Roer et al., 2013; Battini et al., 2014).

Nutritional quality of animal feed varies, and in this analysis the rations contained a higher mean CP and lower mean digestibility in the BP ration when compared to the LF system. The BP system had the lowest ranges in digestibility and CP content, possibly because there was no effect of local climate on farm grown crops in this ration. Reducing the CP intake of the dairy cow diet would help in reducing GHG emissions (particularly N_2O) and UK research has shown that loss of production can be lower than expected (Reynolds et al., 2016). Other environmental and financial strategies to improve nitrogen use efficiency such as home-grown legumes, should have positive consequences for GHG emissions through increased own grown protein and the reduced need for N application from inorganic fertilisers.

The HG system is a comparatively high emitter using economic allocation however, Table 5.11 shows this regime outranked all the other systems using mass allocation because no additional emissions are generated by imported products. In this case mass allocation methods and sensitivity analysis of nutritional variability highlight the benefits of a self-sufficient agricultural system, which may contain positive consequences when incorporating mitigation measures or when moving to more circular economic methods of farming. The HG system also had the lowest area-based emissions as a consequence of the replacement of synthetic N fertilisers by N inputs through biological fixation. In comparison with the HF system where legumes altered the composition of the footprints, however the long term effects of soil conditioning or crop disease prevention were not quantified by carbon footprinting, and carbon sequestration modelling needs to be improved (Sykes et al., 2017) to reflect these other desirable consequences. Mitigation of emissions related to inputs could be achieved in the HG system by reducing pesticide use and using renewable energies on farm.

Over time, improvements in methodology have allowed more precise estimates of emissions arising from agricultural systems. However, during the same period annual global GHG emissions have continued to increase and the interval available to implement any suggested reduction strategies narrows (Boden et al., 2017). Numerous examples can be found in the literature comparing carbon footprints arising from various dairy production methods across the world (Cederberg and Mattsson, 2000; Basset-Mens et al., 2005; Flysjo et al., 2011; O'Brien et al., 2014; Ross et al., 2014) including suggestions for establishing a system emitting less CO_2 per unit product or management type. However, differences in LCA methodology, allocation methods (for milk and meat) or functional unit are said to hinder comparability (Baldini et al., 2017) and a meta-analysis of 30 published LCA's with 87 footprints found no average footprint differences per kg of FPCM (Lorenz et al., 2019). Comparisons of low input grass based, mixed and fully housed intensive dairy systems are valuable to explore uncertainty and mitigation pathways rather than to justify efficacy of one particular method of farming. Between and within countries agricultural practises vary and livestock farming is to some extent, governed by history, culture and tradition (Boogaard et al., 2011). Overall focus should be turned to mitigation of emissions, adaptation to changing climates and improving comparability of LCA's, and communicating uncertainty, however methods of accounting for emissions are also being challenged. Allen et al. (2018) argue that an emissions budget, modelled using the standard $GWP_{100,}$ could be improved upon because this method does not adequately account for the temperature response from short-lived GHGs such as CH_4, and Cain et al. (2019) point out that to achieve the Paris Agreement, long-lived GHGs need to reach 'net zero', whilst short-lived CH_4 emissions should decline to stabilise concentrations. Allen et al. (2018) and Cain et al., (2019) have developed GWP* which accounts for both the larger impact of changes in rates of CH_4 emissions and the lesser impact of stable CH_4 emission on temperature increase. Adopting a GWP* accounting method potentially has dual outcomes for livestock, because even though the warming effect of CH_4 can be stabilised, the sector may be seen as an option to deliver immediate warming reductions. Although fossil fuel and waste sources, are currently estimated to account for nearly 50% of UK anthropogenic CH_4 (NAEI, 2018).

GHG emissions from dairy farming can be mitigated by increasing the longevity of cows within a herd, improving fertility, lowering initial calving age (Garnsworthy, 2004) and by improving digestibility of cow rations (Wilkinson and Garnsworthy, 2017), The increased digestibility could be improved through the reformulation of the diet or through feeding additives and supplements (Knapp, et al., 2011). In less intensive dairy systems, enteric CH_4 emissions can be reduced by increasing yields (Yan, et al., 2010) and technologies such as anaerobic digestion can be effective in reducing emissions from manure storage, with one study reporting reductions of up to 36% (Weiske et al., 2006; Battini et al., 2014). Livestock farming can be associated with other global issues such as ammonia emissions, soil erosion and loss of biodiversity which are out-with the scope of this work but should be considered when developing strategies to reduce GHG emissions (Misselbrook et al., 2016, European Union, 2000). Uncertainty around ongoing availability of phosphorus has been described as an ‘imminent crisis’ that threatens global food security (Blackwell et al., 2019). Phosphorus efficiencies for the dairy systems analysed in Chapter 4 were shown to differ depending on whether or not the non-renewable nature of the resource was taken into consideration.

5.6 Conclusion

Mass and economic allocation methods, and land use functional units, are shown to generate alternatively ranked footprint results. Monte Carlo simulated system footprints considering the effect of variation in feed digestibility and crude protein differed significantly from system footprints using standard methods. Using an economic allocation, a localised home-grown system had the highest C footprint, however, this more self-sufficient system attracted the lowest footprint using mass allocation and attracted the lowest area-based emissions when not considering milk output. It is likely that in developing economy wide reduction in greenhouse gas emissions, mass and area-based assessments of mitigation are most likely to guide the delivery of policy objectives.

Chapter 6

6 Comparative environmental efficiency and trade-offs across diverse dairy systems

6.1 Summary

One pathway towards more sustainable food systems is to increase agricultural efficiency through changes in production systems, whilst simultaneously tackling environmental externalities. This chapter draws on results from previous chapters and focuses on the overall efficiency of the dairy systems by assessing multiple inputs, outputs and undesirable outputs through the application of Data Envelopment Analysis. Externalities such as GHG emissions as well as financial performance and resource use arising from the four contrasting dairy systems and diverse genetic lines are compared in the modelling process. Further environmental indicators of acidification potential (AP) and eutrophication Potential (EP) are calculated and presented in this chapter using a Life Cycle Assessment (LCA) approach. The comparative efficiency of the dairy systems to utilise inputs to offer maximum output whilst minimising undesirable outputs to the environment is investigated and multiple system indicators are visualised using polar charts to assess trade-offs from diverse methods of milk production.

6.2 Introduction

6.2.1 Background

Hansen (1996) suggested that in order for sustainability to drive change within agriculture, a systems approach should be adopted. The concept of sustainability can be described as maintenance of natural, financial and social capital, or as ‘meeting the needs of the present…, …without compromising the needs of the future’ (United Nations, 1987; Daly, 1996). Sustainability can also be framed as a ‘wicked problem’ because essentially there is no solution, and the challenge is management of problems that can be viewed differently depending on the perspective of diverse stakeholders (Peterson, 2013). Using transdisciplinary methods to create new knowledge is described as an essential factor for managing wicked problems and transforming trade-offs (Peterson, 2013).

Increased awareness of food system sustainability issues has encouraged the development of environmental and economic performance measurements to provide a firm basis to understand comparative impacts, trade-offs and to adopt mitigation strategies (SAA, 2013). Whilst the importance of social and economic goals are implicit within sustainability assessments, environmental impacts have attracted more interest (Binder et al., 2010) and the need therefore arises to develop methods to produce a robust set of economic and social indicators (Finkbeiner et al., 2010). Many tools designed to gauge the sustainability of agricultural practises have been developed and whilst some focus on varying assessment levels from farm to product chain others concentrate on a specific sector or indicator theme (Binder et al., 2010; Marchand et al., 2014; FAO, 2013; Olde et al., 2016).

Implementing practises to improve agricultural systems requires an understanding of and capacity to address trade-offs and synergies that can occur between environmental and socio-economic outcomes (Kanter et al., 2018). Assessment of trade-offs can be achieved by comparison of indicators under varied scenarios alongside methods of visualisation that effectively communicate results (Villa et al., 2014; Kanter et al., 2018). Challenges for trade-off analysis include the incorporation of market processes, a need for data alignment and improved stakeholder engagement at each stage of the modelling process (Kanter et al., 2018). The communication of system trade-offs could be improved by incorporating estimates of error and uncertainty for the benefit of policy makers and a need to work with stakeholders to achieve this (Miettinen, 2014; Kanter et al., 2018). Issues around gaps, oversimplification and questionable assumptions surrounding indicators have been found, and optimisation models that avoid weighting bias have been proposed (Carletto et al., 2015; Polasky et al., 2008; Groot et al., 2012). Food system sustainability issues raise further questions such as: What are the most appropriate methods to measure agricultural system performance? Which indicators and functional units should be applied? and, How should trade-offs be presented to policymakers, farmers and industry stakeholders?

6.2.2 System performance indicators

LCA can be considered as a leading tool to estimate environmental effects arising from products and processes (Reap et al., 2008) and climate change can be described as an overarching issue causing global concern, however there are other environmental impacts associated with livestock that should be considered when conducting LCA’s. Dairy farms can be a source of nutrient losses to the wider environment, mainly through livestock excretion (Erisman et al., 2007). Ecological impacts arising from nutrient surpluses include water pollution caused by nitrate leaching, eutrophication of surface waters, soil acidification, and plant damage from ammonia emissions (Amon et al., 2011; Erisman et al., 2007). Eutrophication refers to a state of excessive growth and decay of biomass caused by surplus nutrient inputs to soil or water which can result in oxygen depletion of a water body (O’Neill, 1993) and acidification of soil and surface waters can arise from volatilisation of NH_3 from housed livestock, slurry storage and spreading on land (Leach and Roberts, 2002). Eutrophication potential (EP) and Acidification Potential (AP) are LCA measures that can be expressed in kg PO_4 or NO_3 and kg SO_2 equivalents respectively (SAA, 2013).

Agricultural systems have to be economically feasible in order to deliver sufficient incomes to sustain farming families and their surrounding environment (Zahm et al., 2006). Animal health and farm management can affect both financial and environmental performance of dairy farms (McCarthy et al., 2007; Toma et al., 2013). Body condition score (BCS) and locomotion score (LCS) can be measured on farm using 1-5 scales (Mulvanny, 1977; Manson & Leaver, 1988). BCS is a subjective measure of fat reserves which can be used as a management tool to monitor the health and productivity of the herd (Pryce et al., 2001). Low BCS in dairy cows can be linked with health issues such as claw horn lesions and with reduced digital thickness (Bicalho et al., 2009). Randell et al. (2015) found a greater risk of lameness can be associated with BCS less than 2 and suggest scores of 2.5 or more may be optimal for reducing this risk. Lameness is a significant welfare issue in UK dairy herds particularly in early lactation when it can reduce milk yields and impede fertility (Archer et al., 2010; Baker et al., 2010; Kossaibati and Esslemont, 1997).

Land use, expressed in hectares (ha), is a standard area based functional unit applied in dairy sector LCA’s which have measured a combination of on farm and total ha considering off-farm land (Basset Mens et al., 2009; O’Brien et al., 2011, 2012; Ross et al., 2015). Land is a critical resource that has the dual property of being both a source and a sink of GHGs and this functional unit is used by the IPCC for emissions intensity comparisons (IPCC, 2006; IPCC, 2019). Observed land surface air temperatures continue to rise, and while land use change and intensification have permitted the increased demand for food, degradation and desertification of the soil is a threat to food security (IPCC, 2019).

Use of Data Envelopment Analysis (DEA) has grown in recent years and is a useful approach to measure farm efficiency because weighting is not required and multiple inputs and outputs can be assessed (Emrouznejad et al., 2008; Cooper et al., 2007). DEA is a linear programming technique stemming from operational and economic research used to measure the efficiency of production systems (Farell, 1957; Färe et al., 1994). Charnes, et al. (1978) developed a radial model approach, and Tone (2001) introduced a slacks-based measure (SBM) of efficiency which does not assume proportional reductions of inputs and undesirable outputs. A SBM considers the sum of all slacks within the efficiency score and undesirable outputs are modelled as outputs, rather than as inputs to be minimised such as in Shortall and Barnes (2013). Several studies have applied DEA to assess the environmental efficiency of dairy farms (Bravo-Ureta and Reiger, 1991; Iribarren et al., 2011; Kelly et al., 2012a; Toma et al., 2013).

This chapter use LCA methods to assess the overall efficiency of diverse dairy systems by assessing multiple inputs, outputs and undesirable outputs through the application of DEA. GHG emissions, acidification potential (AP) and eutrophication potential (EP), as well as financial performance and resource use arising from the four contrasting dairy systems and diverse genetic lines are compared in the modelling process. The comparative efficiency of the dairy systems to utilise inputs to offer maximum output whilst minimising undesirable outputs to the environment is described as a measure of performance. A holistic expression of multiple system indicators is visualised using polar charts to assess and present trade-offs from multiple methods of milk production.

6.3 Methods

6.3.1 Data

Data in this chapter originates from the dairy systems experiment described in Chapter 5. Raw data and input variables used to calculate GHG emissions applied in the efficiency analysis were described in Chapter 5 and methods and inputs used to estimate eutrophication and acidification potentials and are described in this chapter. Boundaries applied in this study are 'cradle to farm gate' which include all stages of production from acquisition of farm inputs and raw materials until when milk or animals leave the farm. The standard functional unit related to dairy LCA's of fat and protein corrected milk (FPCM) is applied using the following equation (IDF, 2010);

$$\text{FPCM} = \text{Production (kg/year)} \times [0.1226 \times \text{Fat (\%)} + 0.0776 \times \text{Protein (\%)} + 0.2534]$$

The impact categories applied here as undesirable outputs in the efficiency analysis are; GHG emissions calculated in Chapter 5 and expressed in kg CO_2e, Eutrophication Potentials (EP) that are expressed in kg PO_4e, and emissions relating to Acidification Potentials (AP) expressed in kg SO_2e , with equivalence factors shown in Table 6.1. Annual inventories of the eight dairy systems using data from 5 system years for HF and LF (2006-2010) and 4 system years (2012-2015) for HG and BP treatments are described in detail in Chapter 5.

Table 6-1 Equivalence factors used in LCA to calculate global warming, eutrophication and acidification potentials

Impact Category	Equivalent factors	
Global Warming Potential	1 kg carbon dioxide (CO_2)	1 kg CO_2e
	1 kg methane (CH_4)	25 kg CO_2e
	1 kg nitrous oxide (N_2O)	298 kg CO_2e
Eutrophication Potential	1 kg phosphate (PO_4)	1 kg PO_4e
	1 kg ammonia (NH_3)	0.35 kg PO_4e
	1 kg nitrate (NO_3)	0.095 kg PO_4e
Acidification Potential	1 kg sulphur dioxide (SO_2)	1.0 kg SO_2e
	1 kg nitrogen Oxides (NO_x)	0.5 kg SO_2e
	1 kg ammonia (NH_3)	1.6 kg SO_2e

Huijbregts (1999)

6.3.2 Eutrophication and acidification potential

Eutrophication potential (EP) and Acidification Potential (AP) are calculated in AgRECalc using the method described in the LCA Handbook (Guinee et al., 2002). Inventory data described in Chapter 5 is applied and impacts are expressed in kg PO_4 and kg SO_2 equivalents, respectively. EP and AP of the diverse dairy systems are measured by estimating a range of sources that include deposition, storage, spreading of livestock manure on farmland, and embedded emissions in the use of purchased inputs such as feeds. Factors used to estimate the EP and AP of emissions embedded in the dairy system diets are shown in Table 6.2. Other embedded missions mainly stem from imported fertilisers, fuel and bedding. Emissions of NH_3, NO_x and PO_4 stem from deposition and storage of livestock manure, and from the applications of fertilisers. Volatilised and leached N and P from fertilisers also contribute to AP and EP, as do pesticide and fuel use.

Table 6-2 Dairy system feed component EP and AP

Diet	Component	EP g PO_4 e /kg	AP g SO_2 e /kg
Low Forage	Wheat Grain	3.41	10.2
	Sugar Beet Pulp Molasses	1.87	2.89
	Soya Bean Meal	15.4	9.10
	Distillers Grains (Wheat)	0.83	0.01
	Soya Hulls	8.35	5.90
	Protected Fat	1.41	4.90
By-product	Straw	2.86	7.33
	Sugar beet pulp molasses	1.87	2.89
	Breakfast Cereal	3.41	10.9
	Distillers Grains (Wheat)	0.83	0.01
	Biscuit Meal	0.03	0.13
	Wheat Distillers Dark Grains	5.21	17.0
	Soya Bean Meal	15.4	9.10
	Molasses Cane	1.44	3.8
	Protected Fat	1.41	4.90
High Forage	Rapeseed Meal	5.21	12.0
	Distillers Grains (Barley)	0.83	0.01
	Distillers Grains (Wheat)	0.83	0.01

Factors applied in the AgRECalc model are IPCC Tier II for livestock and manure management and Tier I for fertiliser and crop residues N_2O (IPCC, 2006). Ammonia

(NH_3) and nitrogen oxides (NO_x) emissions arise through volatilised and leached N from stored manure, and run off from manure application, and from N fertiliser application. P excreted from dairy cows was estimated to be 19.2 kg /cow with a 1% leaching rate. N excretion from dairy cows was modelled at a maximum 151.6 kg / head /year (IPCC, 2006). The EP of embedded emissions in purchased fertilisers was modelled at 0.0005, 0.00074, and 0.0003 kg PO_4^{3-} / kg of N, P and K respectively and a factor of 0.015 was used for pesticides. Diesel combustion was estimated to emit 0.026 kg of nitrogen oxide (NO_x) and 0.00068 kg of SO_2e per litre.

6.3.3 Environmental efficiency

Data envelopment analysis (DEA) can be used to estimate the comparative efficiency of production systems and the background to efficiency modelling is described in Chapter 4. In Chapter 4 undesirable output orientated DEA models were employed to assess the phosphorus efficiency as a non-renewable resource. DEA analysis in this chapter utilises an additive model approach as discussed in Chapter 1 (Tone, 2001; Cooper et al., 2007). Data were processed in Excel and modelling was carried out in R v.3.3.3 (Core R, 2019) using the package additiveDEA (Soteriades, 2017). Production inputs and outputs from the dairy systems alongside the undesirable outputs of GWP, EP, and AP are considered to assess comparative efficiency. Inputs include on farm and off farm land, imported fertilisers, grown and purchased feeds, milking cows, young stock with descriptive statistics for the dairy systems shown in Table 6.3 for Select merit and Control merit cows. Outputs consisted of FPCM, and undesirable outputs were GWP, EP and AP (Table 6.3).

Additive efficiency models, such as those used by Iribarren et al., (2011) were applied in this chapter to assess the efficiency of the systems to produce milk with the least amount of inputs and undesirable outputs. Additive DEA models were found to be more appropriate for use when comparing farm efficiency (Soteriades et al., 2015). A Range Adjusted Measure (RAM) model which weighs slacks by the ranges of inputs and outputs was used (Cooper et al., 1999; 2001). The RAM efficiency model is translation invariant and can cope with zero values, such as that would be found when measuring amounts of N fertiliser purchased for BP dairy systems and undesirable outputs, such as GHGs are denoted as negatives to be minimised in the model. Each farm year is treated as a decision-making unit (DMU) and 36 system years in total are used to measure the comparative ability of the DMU's to minimise inputs given a determined level of output and undesirable output.

Table 6-3 Descriptive statistics of dairy system inputs and outputs applied in the DEA model

	LFS	BPS	HFS	HGS	LFC	BPC	HFC	HGC								
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Inputs																
Land use (ha)	74.5	6.95	59.5	4.07	63.4	10.57	78.8	2.54	73.2	5.71	52.6	5.36	65.6	9.36	69.1	8.04
N fertilizer (tonnes)	3.2	1.51	0.0	0.0	4.6	2.57	4.7	6.17	3.2	1.20	0.0	0.0	4.7	2.99	4.0	8.28
Grown feed (tonnes)	767	87.2	0.0	0.0	717	82.4	793	48.9	751	88.3	0.0	0.0	742	68.0	679	56.2
Feed import (tonnes)	558	21.2	796	48.8	345	26.6	223	28.1	561	12.2	714	65.7	370	27.9	212	14.9
Milking cows	45	3.9	50	2.4	51	4.3	55	2.5	50	0.7	52	2.1	53	1.1	55	2.8
Young stock	43	5.1	42	4.7	47	4.8	45	6.1	55	6.5	40	7.8	61	6.0	42	7.7
Outputs																
FPCM (tonnes)	541	62.8	529	28.2	447	67.2	431	56.3	464	21.1	403	48.3	404	30.8	347	13.7
GHG CO$_2$e (tonnes)	534	74	567	53	533	85	537	17	541	54	499	41.9	558	63	482	28
EP PO$_4$e (tonnes)	4.4	0.6	3.6	0.3	4.7	0.8	4.8	0.3	4.2	0.3	3.2	0.3	5.2	0.8	4.7	0.2
AP SO$_2$e (tonnes)	10.0	1.4	9.3	0.5	8.8	1.4	9.8	0.4	10.2	1.0	8.9	0.7	10.0	1.4	9.0	0.3

Genotype: C = Control, S = Select; Feed systems: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown

[c]SD = Standard deviation, FPCM=Fat and protein corrected milk

The RAM model applied (Cooper et al., 1999, 2001) can be described as follows;

Suppose there are n DMU's each utilising m inputs or environmental impacts, to produce s desirable outputs, denoted as,

x_i (i = 1, … , m), y_r (r = 1, … , s) respectively.

The RAM modelled inefficiency score of the *j*th DMU, denoted by DMU$_o$ can be defined by the linear program (Cooper et al., 1999):

$$\rho * = \frac{\max}{\lambda_j, S_{\iota o} S_{ro}} \frac{1}{m+s} (\sum_{i=1}^{m} \frac{s_{io}}{R_i} + \sum_{r=1}^{s} \frac{s_{ro}}{R_r})$$

subject to

$$x_{io} = \sum_{j=1}^{n} x_{ij}\, \lambda_j + s_{io} \qquad i = 1, \dots, m$$

$$y_{ro} = \sum_{j=1}^{n} y_{rj}\, \lambda_j + s_{ro} \qquad r = 1, \dots, s$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$s_{io} s_{ro} \lambda_j \geq 0 \ (i = 1, \dots, m, r = 1, \dots s, j = 1, \dots n),$$

where

x_{io} and y_{ro} are inputs and outputs and s_{io} and s_{ro} are the corresponding input and output slacks from each of the DMU's, λ_j is a vector denoting benchmark DMU's when positive. An input slack corresponds to an overuse of certain inputs, and an output slack would indicate a DMU could have produced higher output with the corresponding input. Five runs of the model were applied to consider any differences between EI's and also whether land resource as an input changes the ranking of the systems. Data processing was carried out in Excel and the post hoc Kruskal-Wallis and Dunn tests were applied in R to test for stochastic dominance amongst the dairy systems.

6.3.4 Analysis of trade-offs

Management and animal welfare can effect financial and environmental performance of dairy farms and even though LCA is a useful tool when considering environmental impacts exogenous variables such as biodiversity status and animal health cannot easily be quantified in the life cycle inventory. The analysis of trade-offs allows further system variables to be considered, that are relevant to particular farm production scenarios and the following section describes methods used to calculate financial and animal health indicators.

Gross margin analysis was undertaken to provide an outline financial comparison of the four feeding regimes to directly compare costs stemming from diverse feeding regimes and incomes from milk sales. Feed components contained within each of the diets were costed with average industry values for October 2016 (pers. com Karen Stewart, SRUC). Total purchased feed costs for the respective dairy systems were estimated by cost per tonne of TMR components for the LF, HF and BP diets and calculating at herd level annually in AgRECalc. The estimated cost for purchased feeds in each diet was £88 and £139 per tonne for LF and BP systems, respectively. Crop costs were estimated using the farm management handbook (SAC, 2018) and fertiliser costs were gathered from AHDB (2018). A standard liquid based schedule was applied to monthly milk production from each system with a base value of 30.0p/l and bonuses or penalties applied for constituent levels, in this case with minimums of 37.0g/kg of butterfat and 30.0g/kg of protein. Payments for hygienic quality as well as a volume bonus were applied at £0.034 and £0.006 per litre produced. An outline of dairy system financial performance used in the analysis of trade-offs are shown in Table 6.5.

Table 6-4 Descriptive statistics of daily feed intake, yields, BCS and LCS

Feed system	Merit	DMI	Daily Yield	Body Weight	BCS	Min BCS	Max BCS	LCS
By-product	Select	22.8	33.9	622	2.08	0.5	4.0	2.40
Low Forage	Select	20.5	35.4	638	2.17	0.5	4.3	2.30
High Forage	Select	14.8	28.0	625	1.97	0.5	3.5	2.18
Home-grown	Select	14.0	25.6	586	2.02	0.5	4.3	2.23
By-product	Control	20.5	29.5	607	2.21	0.5	4.0	2.55
Low Forage	Control	18.3	31.3	620	2.32	0.8	4.0	2.33
High Forage	Control	13.6	25.1	600	2.12	1.0	3.8	2.13
Home-grown	Control	13.2	23.6	587	2.14	0.5	4.3	2.21

DMI= Dry matter intake kg, BCS = Body condition score, LCS = Locomotion score

Sub-optimal herd health affects both environmental efficiency and financial performance of a herd. Body condition score (BCS) and Locomotion score (LCS) are applied as indicators in the analysis of trade-offs because they are routinely used on farms. Body condition score (BCS) and locomotion score (LCS) were measured weekly by trained farm technicians using 1-5 scales (Mulvanny, 1977; Manson & Leaver, 1988). BCS and LCS data for the dairy systems applied in the trade-off analyses were extracted directly from the database and descriptive statistics are shown in Table 6.4 alongside daily yields and dry matter intakes.

Dairy system indicators representing financial, environmental, health and land use are drawn together to form a set of variables used to visualise comparative performance from multiple perspectives. Visual communication of trade-offs in a straightforward manner is key to allowing the interpretation of interactions between indicators and expressing scenarios (Miettinen, 2014; Kanter et al., 2018). Polar charts are applied in R to visualise trade-offs in order to explore pathways to sustainability and dairy system indicator are shown in Table 6.6. The indicators were each normalised across their respective ranges to present the visualisation. This meant that higher performing systems within each category were represented by a larger volume on the polar chart.

Table 6-5 Indicators applied in trade-off assessment

Indicator	BPC	BPS	LFC	LFS	HFC	HFS	HGC	HGS
Income (ppl)	29.4	30.47	30.01	30.65	30.58	30.73	30.51	31.06
Feed costs (ppl)	21.3	19.84	18.52	16.82	13.24	11.28	7.30	6.96
BCS (mean)	2.21	2.08	2.32	2.17	2.12	1.97	2.14	2.02
LCS (mean)	2.55	2.40	2.33	2.30	2.13	2.18	2.21	2.23
Land use (ha)	53	60	73	75	66	63	69	79
GHGs kg CO_2/kg FPCM	1.24	1.07	1.13	0.95	1.33	1.15	1.28	1.16
EP kg PO_4e/kg FPCM	0.008	0.007	0.009	0.008	0.013	0.011	0.013	0.011
AP kg SO_2e/kg FPCM	0.022	0.018	0.022	0.018	0.025	0.020	0.026	0.023

BCS= Body condition score, LCS = Locomotion score, EP =Eutrophication potential, AP = Acidification potential

Genotype: C = Control, S = Select; Feed systems: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown

Table 6-6 Income from milk, fat and protein sales and modelled variable, purchased feed and crop costs

Income / Cost	BPC	BPS	LFC	LFS	HFC	HFS	HGC	HGS
Yield per cow (l)	8553	10927	9480	10836	7504	8434	6509	7462
Fat bonus ppl	-0.007	0.001	-0.001	0.003	0.003	0.004	0.002	0.006
Protein bonus ppl	0.000	0.003	0.001	0.004	0.003	0.004	0.003	0.004
Total milk sales, 30ppl base	£513,180	£655,620	£568,800	£650,160	£450,240	£506,040	£390,540	£447,720
Fat bonus / penalty £	-£11,568	£3,269	-£1,426	£5,441	£4,065	£6,023	£3,132	£9,293
Protein bonus	£633	£7,025	£1,620	£8,625	£4,640	£6,371	£3,571	£6,599
Income milk, ppl	£0.294	£0.305	£0.300	£0.306	£0.306	£0.307	£0.305	£0.311
Feed costs, ppl	£0.21	£0.20	£0.19	£0.17	£0.13	£0.11	£0.07	£0.07
Gross margin over feed ppl	£0.08	£0.11	£0.11	£0.14	£0.17	£0.19	£0.23	£0.24
Gross margin % income	27.3%	34.9%	38.3%	45.1%	56.7%	63.3%	76.1%	77.6%

Genotype: C = Control, S = Select; Feed systems: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown

6.4 Results and discussion

6.4.1 Eutrophication and Acidification Potentials

Eutrophication and acidification potentials were assessed as indicators of localised air and water pollution that are not communicated within carbon footprinting results. Table 6.3 shows EP and AP applied in the efficiency analysis expressed in terms of absolute outputs of PO_4e and SO_2e in tonnes and Table 6.6 shows EP and AP results expressed per kg of FPCM. Dairy system EP averaged 10.0g PO_4 / kg FPCM and ranged from 6.4 to 14.8 g, and AP ranged from 14.6 to 26.6 g SO_2 / kg FPCM and averaged 21.6 grams. Average EP and AP results were found to be similar to those reported in a range of other studies reported by Poore and Nemecek (2018).

System performance results in terms of production output for EP show that the housed BP and LF systems attracted less surplus nutrients than the grazed systems due to reduced deposition and application of manure and comparatively greater yields of milk. Manure was exported from the BP system, and the EP in this system mainly stems from NH_3 volatilisation at storage and embedded emissions from purchased feeds at 48% and 52% of the total, respectively. Compared to the BP system, the LF system EP attracted less volatilisation at storage and instead the N volatilised and leached at manure application, and additionally at fertiliser application. In the grazed HF and HG systems EP from embedded emissions decreased and manure storage and application of fertiliser and manure emissions increased and accounted for 50% and 40% of the totals in the HG system, respectively. Ranked dairy systems performance for AP were comparatively similar to EP because of the volatilisation of NH_3 and embedded emissions in feeds that contribute to both environmental impacts. Across the systems absolute output of PO_4 e averaged 4.4 tonnes per year and ranged from 2.9 to 6.1 tonnes, and SO_2 e outputs ranged from 7.8 to 11.7 tonnes and averaged 9.5 tonnes. Emissions from fuels have comparatively little impact towards EP and AP across the dairy systems.

6.4.2 Efficiency analysis

Five runs of the DEA model were applied to assess the efficiency of the systems according to environmental focus or whether or not the input of total land altered the performance score. Model output averaged efficiency scores are shown in Table 6.6 and descriptive statistics across all model scores in Table 6.7 shows that the select merit cows were found to be more efficient than Control merit in all systems. Control merit cows in the housed LF and grazed HF system were not as efficient as the novel systems, however Control systems did have the capacity to be efficient in some years, apart from LFC (Table 6.8).

Table 6-7 Dairy system average efficiency scores by DEA model focus

	LFS	BPS	HFS	HGS	LFC	BPC	HFC	HGC
GHGs, EP, AP	1.00	0.97	1.00	1.00	0.83	0.76	0.87	0.96
GHGs	1.00	1.00	0.98	1.00	0.89	0.95	0.88	0.98
EP	0.99	1.00	0.94	1.00	0.85	0.96	0.78	1.00
AP	1.00	1.00	0.95	1.00	0.86	0.95	0.83	0.98
No Land	0.99	0.99	0.98	1.00	0.83	0.95	0.90	1.00

HF=High forage, LF = Low forage, BP = By-product, HG = Home grown

The Select merit in the HG system was consistently more efficient in all model types albeit by a small amount and performed slightly better that the housed LF and BP systems in EP for LF and, unsurprisingly, when land was not considered (Table 6.7). Using absolute values of dairy farm inputs and outputs, with environmental externalities in this analysis highlights that a more self-sufficient system with locally grown proteins can be as efficient as a high producing system with greater yields of milk. A Control merit cow was, on average, more efficient in a HG system. Overall, the efficiency scores are high which can be expected in a RAM model if ranges that the slacks are normalised against are small (Soteriades et al., 2016).

Table 6-8 Efficiency score descriptive statistics

Diet	Genetics	Minimum	Maximum	Mean	Std. Dev
Low Forage	Select	0.96	1.00	0.998	0.008
By-product	Select	0.87	1.00	0.993	0.029
High Forage	Select	0.86	1.00	0.971	0.050
Homegrown	Select	1.00	1.00	1.000	0.000
Low Forage	Control	0.73	0.91	0.850	0.037
By-product	Control	0.64	1.00	0.914	0.111
High Forage	Control	0.69	1.00	0.848	0.104
Homegrown	Control	0.89	1.00	0.981	0.035

A Kruskal-Wallis test was carried out in R to compare the efficiency scores across the systems and there was evidence to show a significant difference between the mean ranks of the dairy systems ($p<0.001$). Specific differences between the management regimes were identified using Dunn' test, and results showing z statistics of significantly different system efficiency scores ($p<0.05$) are provided in Table 6.9. Results show that significant differences mainly occur between both diet and genetic merit. There was no significant difference found in ranked efficiency score between HGS and BPS, LFS or HFS systems.

Table 6-9 Dunns pairwise test results for differences in system efficiency scores with ($p<0.05$)

Pairwise system comparison	z statistic
BPC-HGS	-3.199006
BPC-LFC	3.293484
BPC-LFS	-3.206108
BPS-HFC	5.426484
BPS-LFC	6.344298
HFC-HFS	-4.481164
HFC-HGC	-4.600451
HFC-HGS	-5.747719
HFC-LFS	-5.920370
HFS-LFC	5.454653
HGC-LFC	5.518266
HGS-LFC	6.665533
BPC-HGS	-3.199006
LFC-LFS	-6.893859

6.4.3 Financial indicators

Gross margin evaluations were carried out by calculating income from milk sales based on monthly fat and protein production from the dairy systems. Results show a liquid based schedule generates a range of potential incomes from milk sales at 29.4 to 31.1 ppl, depending on diet and genotype (Table 6.5). Housed systems with higher yields did not guarantee maximum incomes per litre because of differences in milk quality (Table 6.5). The grazed HF and HG systems generated higher incomes per litre, because of greater bonuses for constituents, with the HGS system attaining the greatest income from fat sales. Protein sales were higher in the housed systems than the grazed systems and C merit cows attracted less income from protein (Table 6.5).

For the housed BP and LF systems the C and S merit herds in both feed types generated similar incomes from base liquid sales, however, milk containing low butterfat percentages equated to penalties for below minimum fat content in Control merit cows, and the LFS system generated the highest total and ppl income. Costs were greatest within the BP system because of the price of feed components within the TMR. Modelled income for the BP system would be improved if all slurry exported was sold with a financial value that was equivalent to manufactured fertiliser. Differences in margins over feed costs in this analysis, show that greater profits generated from higher yields come at the expense of income per litre sold which was found in the comparison of the LF and HF systems using the MDSM (March et al., 2017).

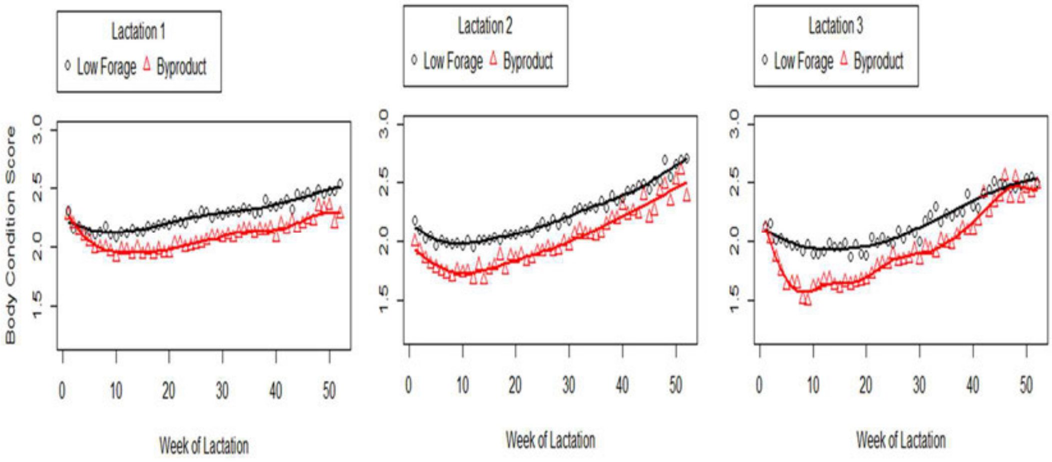


Figure 6.1 Weekly body condition scores in the LFS and BPS systems partitioned by lactation

6.4.4 Health indicators

Herd health indicators were calculated for each system to evaluate the impact on cow health after moving from a LF diet to a BP diet, and from a HF diet to an HG diet. In the housed LF and BP systems, on average, across each lactation, BCS's within the BP group fell to a lower level than those in the LF group (Table 6.4). BCS's and LCS's both differed significantly between the LF and BP systems p<0.001. Locomotion scores were, on average, higher in the BP system and ranged from 1-5 whereas LCS ranged from 1-4 in the LF system. Figure 6.1 illustrates weekly BCS averages partitioned by lactation for BPS and LFS cows to highlight differences in condition score minimums and ranges between the two housed feed systems. Condition scores were on average higher in the HG system than the HF system and on average across all dairy systems Control merit cows attained higher BCS's than Select merit cows, which is possibly because the high production merit cows are partitioning more fat reserves to produce milk.

6.4.5 Trade-offs

Graphics used to visualise trade-offs across agricultural indicators range from conventional tables, bar charts, box plots and scatter plots to spider, radial and petal diagrams (Tuomisto et al., 2012; Bommarco et al., 2012; Kanter et al., 2018; Foley et al., 2011). Petal diagrams were used by Foley et al. (2005, 2011) to compare ecosystem service provision and assess the performance of agricultural systems against environmental and food security goals. Flower diagrams have been used to illustrate the impact of human activities (Steffen et al., 2015) and Raudsepp-Hearne et al. (2010) quantified ecosystem services across landscapes to illustrate trade-offs. Polar charts are similar to petal plots and are used in this analysis to communicate the results in an uncomplicated way.

Multiple indicators can be used to represent financial, environmental, health and land use attributes of the diverse dairy system to assess the effect of novel diets on multiple attributes of performance and to describe trade-offs across the systems and genetic merit (Table 6.5). The multiple indicators presented in Table 6.5 were ranked and are shown in Table 6.10 which highlights that none of the systems outperform all the other in every indicator. Every dairy system shows a comparatively weak performance in one or more indicators and an equally weighted mean of the ranks shows best to worst performance of LFS, HFS, BPS, LFC, HGS, BPC, HFC and HGC (Table 6.10).

Multiple systems and indicators can be interpreted visually, and Figure 6.2 shows an example of a polar chart representing a theoretical best performance with a full section for every indicator. In this analysis GHGs, EP and AP are expressed per kg of FPCM the results are comparative to each of the eight dairy systems, however a best performance could be constructed to represent targets for in each indicator category (for example GHG emissions). Figure 6.2 also shows the BPS system indicator results and highlights how this dairy management regime performs better in land use, EP and AP, however, performs comparatively less well on feed costs and average BCS. Financial and environmental indicators are expressed in relation to milk outputs whilst land use is expressed as total hectares of on-farm and off-farm land.

Table 6-10 Ranked indicators

Indicator	BPC	BPS	LFC	LFS	HFC	HFS	HGC	HGS
Income (ppl)	8	7	6	3	4	2	5	1
Feed costs (ppl)	8	7	6	5	4	3	2	1
BCS (mean)	2	6	1	3	5	8	4	7
LCS (mean)	8	7	7	5	1	2	3	4
Land use (ha)	1	2	6	7	4	3	5	8
GHGs kg CO_2 / kg FPCM	6	2	3	1	8	4	7	5
EP kg PO_4 / kg FPCM	2	1	4	3	7	5	8	6
AP kg SO_2 / kg FPCM	5	1	4	2	7	3	8	6
Mean rank	5.0	4.1	4.6	3.6	5.0	3.8	5.3	4.8

Genotype: C = Control, S = Select; Feed systems: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown

The eight dairy systems are presented together as polar charts in Figure 6.3 which shows that differences in management regime lead to differences in performance across multiple indicator types. Figure 6.3 shows the dairy systems perform comparatively better or worse depending on the indicator of choice. The C merit systems generally exhibit a similar overall shape with a reduced volume when compared to the S merit system of that feed type, apart from mean BCS which is comparatively better in the C merit systems and is a consequence of breeding.

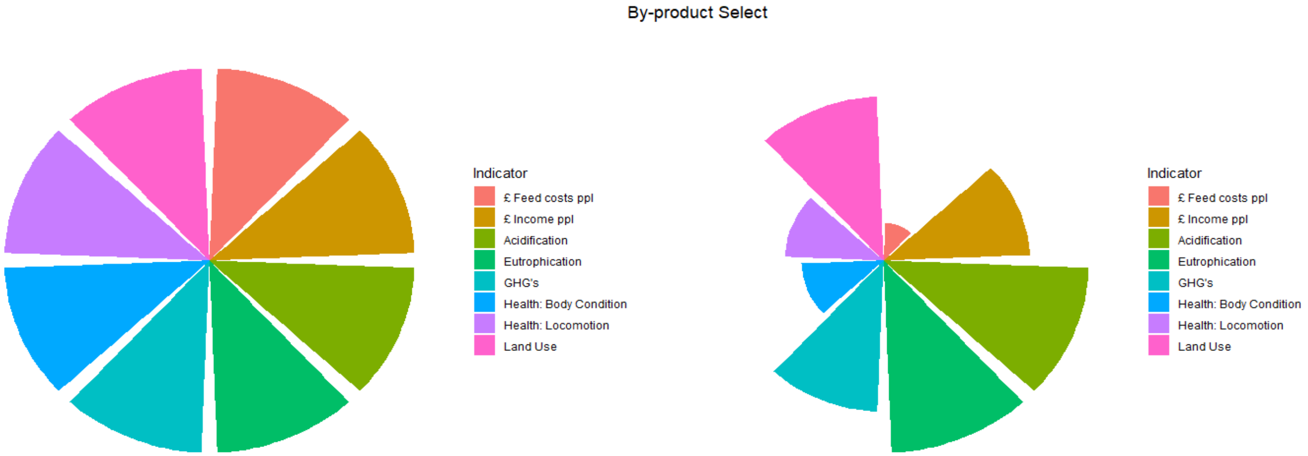


Figure 6.2 Best performance example and by-product system polar charts

The polar charts shown in Figure 6.3 could be used as a basis for stakeholders and policy makers to target appropriate system performance improvements whilst taking into consideration a wide range of other system performance indicators and perspectives. Performance improvements could be brought about through management changes, or technology aimed at increasing income, improving health, lowering costs or reducing environmental impacts. For example, the HFS system could target a comparatively low BCS by changing calving pattern from AYR to a block system which would align with the grazing season. This change in management could possibly lead to improved health increased yields and thus fewer GHG emissions per unit product.

The HG system was shown to be efficient in terms of inputs and outputs and performs comparatively well in terms of income and feed costs, however strategies to reduce GHGs, AP and EP could focus on land and soils such as by improving application of fertiliser and manure through precision technologies and improving forage quality would also be beneficial. The LF system performs comparatively well for income and environmental impacts and less well in land use, feed costs and health. Land use is comparatively high in the LFS system because of the amount of soya bean meal in the ration. Land use could be improved by integrating a home-grown protein into the crop rotation, which may also lead to lower feed costs and reduce N fertiliser input.

The BP system is a novel milk production method that would not normally be practised although there have been calls to feed livestock only on ‘ecological leftovers’ and pressures on land as a resource are forecast for the future (Garnet, 2014). In comparison to the LF housed system, Figure 6.3 shows that feeding high production merit cows non-human edible feedstuffs and no forage led to comparatively higher feed costs and GHG emissions and lower income from milk sales and mean BCS. The BPS system performed comparatively well in land use and EP because of the allocation of land to by-products and the caveat of exportation of all manure.

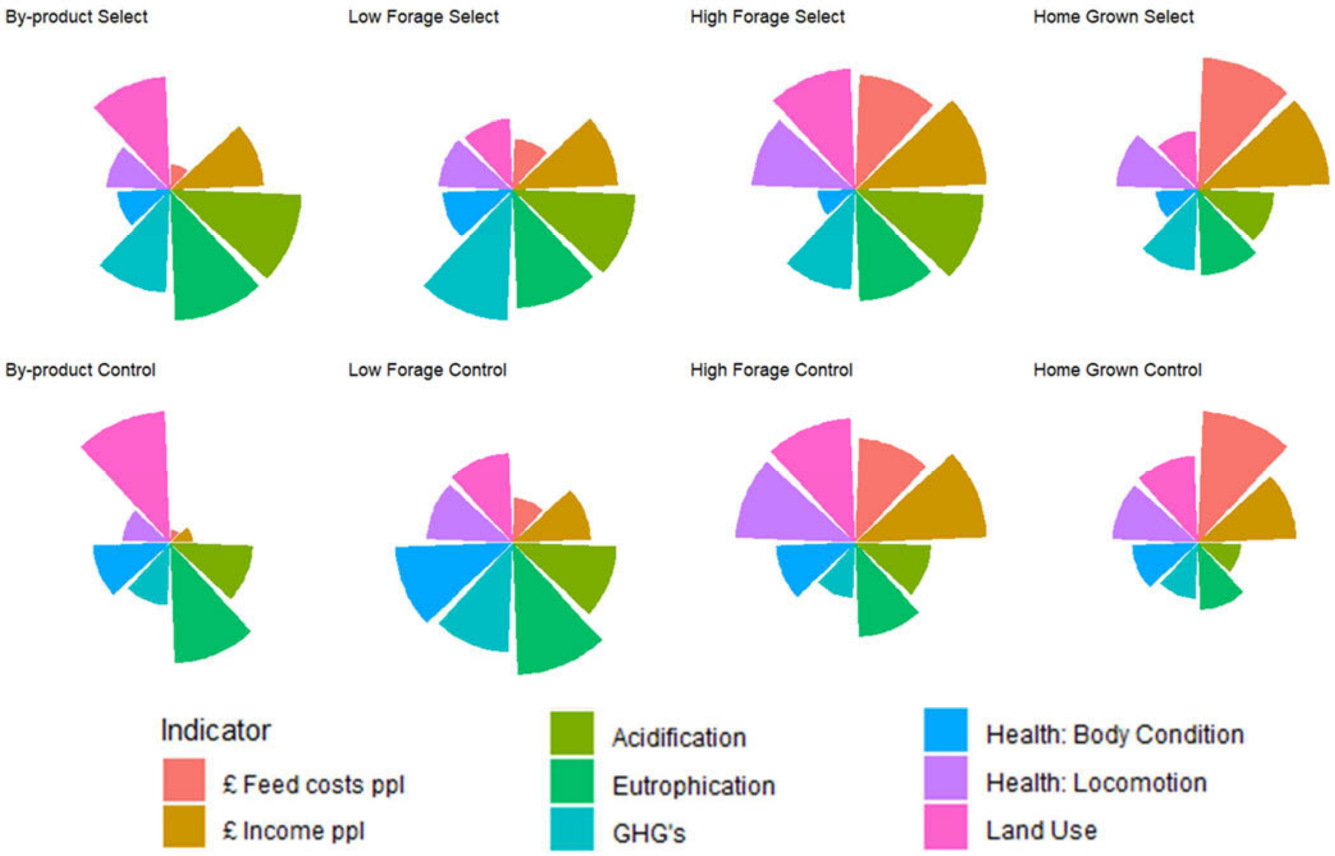


Figure 6.3 Dairy system performance comparison across multiple indicator types

Using DEA as a measure of comparative efficiency of the dairy systems has shown that the high production Select merit systems to be more efficient than the average merit in all feeding regimes. A novel self-sufficient dairy system was shown to be as efficient as housed and grazed systems similar to those currently practised in the UK. The home-grown regime has attributes of a circular system through reduced imported feed and fertiliser inputs. Moves towards circular economies are being encouraged through reduction, reuse and recycling of resources and legislation is currently being proposed in Scotland (Scottish Government, 2019). A circular dairy regime could adopt strategies such as closing nutrient cycle loops, water reuse and improving soils and land management. Dairy farming incorporates circular practises when manure from digested grass is returned to the soil as nutrients however diverse dairy systems require alternative transformation approaches, and research has been called for to provide in-depth analysis of pathways showing economic, environmental and social performance (de Wit et al., 2016). The polar charts show consequences from multiple perspectives of moving from commonly practised, to novel milk production regimes determined by theoretical future pressures and competition between humans and animals to utilise land. A holistic expression of multiple system indicators was able to represent multiple and diverse performance measures. Trade-offs from multiple methods of milk production were found within and between feed systems and indicator types.

The polar charts in Figure 6.3 could be developed further through the addition of indicators such as water use, animal welfare or use of antibiotics. Polar charts could also be extended and subdivided to provide finer detail. Extended polar charts could be used to identify more specific areas of improvement, for example a range of financial benchmarks could be displayed, or environmental performance measures of GHGs by type or by emission source. Polar charts could be expanded with further layers to consider targets applied to performance indicators. Representing aims such as GHG emissions reductions would provide an additional reference measure of overall performance.

6.5 Conclusions

Efficiency analysis has shown that when a suite of undesirable outputs are considered high production Select merit systems were more efficient than average merit cows regardless of feed type. A novel home-grown dairy system was shown to be as efficient as housed and grazed systems similar to those currently practised in the UK. Using an LCA approach and multiple dairy system indicators comparative merits and trade-offs from multiple methods of milk production were clearly shown.

Chapter 7

7 General Discussion

7.1.1 Thesis Objectives

This cross-disciplinary research provides a holistically measured comparison of diverse genetic lines of Holstein Friesian cows within novel and conventional UK dairy farming systems by employing a range of indicators and modelling techniques alongside a visual representation of the milk production regimes. Sensitivity and uncertainty surrounding financial and environmental measurements is highlighted to communicate the mutable nature of profitability and environmental outcomes when measuring farm performance. Trade-offs and synergies associated with the production of milk within current and possible future dairy systems are assessed to illuminate potential areas of focus to mitigate externalities or improve efficiency. Quantification of environmental externalities arising from agricultural systems is of interest for both scientific and social reasons, so that types, sources, and amounts of undesirable outputs can be understood, managed and reduced.

The first objective was to assess the effect of genetic line, feeding system and replacement rate on production, costs, income and profitability and results showed that irrespective of dairy management system, genetic selection for increased production leads to improvement in financial performance, when compared to an average UK merit. Model outcomes illustrated that obtaining greater yields from average merit cows at the expense of high costs are not financially sustainable, especially under fluctuating milk prices which are currently the norm. Management of the dairy farm has a clear effect on profitability as herd replacements and reproduction decisions can affect the lifetime production of a cow and alter the age profile of a herd. The second objective was to assess the effect of genetic line and feeding system on the environmental performance of milk production systems and this was carried out by identifying multiple environmental externalities. Performance rankings of the systems differed depending on modelling method, choice of indicator and functional unit and also whether or not uncertainty of nutritional inputs were included. The final objective to assess the comparative efficiency of the systems again highlighted that genetic selection for increased production led to higher system efficiencies and improved environmental performance compared to an average merit across all environmental outcomes.

Quantification of environmental externalities highlights differences in perceived system efficiency depending on model focus. Unsurprisingly systems of milk production that involve a lower throughput of phosphorus attract higher eco-efficiency scores when future generations are considered, and the non-renewable nature of the nutrient P accounted for. High yields attainable in housed dairy systems farming with high producing merit animals incur fewer GHGs per kg product, however, results show the difference in emissions between the housed and grazed S merit systems is not large (~ 0.2 kg CO_2 / kg). Uncertainties within system inputs, emission factors and formulas demonstrate a great deal of variation surrounding carbon footprint results. The sensitivity of footprinting model outputs should always be communicated when presenting results. Annual footprint calculations should be used as a basis for mitigation because a suite of GHG types are attributed to agriculture, livestock and milk production.

7.1.2 Mitigation of GHG emissions

In the decade between 2005 and 2015, the global dairy herd, and milk production grew, by 11% and 30% respectively, and dairy sector GHG emissions rose by 18% (FAO, 2019). UK average emissions of 1.2 kg CO_2e / kg FPCM are at the lower end of a wide range of GHG intensities associated with milk production globally, nevertheless mitigation is required for this sector to contribute to national targets (FAO, 2019). At the same time, effects of anthropogenic climate change are already challenging agriculture across the globe through changes in seasonality and extreme weather events (IPCC, 2014). In the EU, observed climate change has impacted on the availability of food through decreased yields of wheat, barley and marginal increases in yields of sugar beet and maize (Moore and Lobell, 2015). Impacts of climate change on livestock production include water availability, disease, forage availability, quality and growth and also, animal health and reproduction (Rojas-Downing et al., 2017). Temperature increases are predicted to have a positive impact on livestock production in temperate regions, such Canada and North America, and a negative impact in more arid regions in western Africa and Australia (Rojas-Dowling et al., 2017; Boone et al., 2018). Livestock production globally faces the dual challenges of mitigating emissions and adapting to a changing climate.

Dairy system footprints presented in Figure 5.3 highlight differences in emission source type which should be considered when assessing mitigation potentials and strategies. Emissions from livestock and manure management can be reduced in all dairy systems through measures such as nutritional strategies aimed at lowering enteric CH_4 and N excretions, and also slurry separation and anaerobic digestion (Wattiaux et al., 2019). At dairy system level reducing emissions from energy and fuel, perhaps through renewable energies used to generate electricity and run machinery, such as bio-methane powered tractors would offer greatest potential in HG systems. Emissions of N_2O from land and crops can be lowered through reduced inputs to soil and also measures that improve soil organic matter or increase soil carbon. These include optimal application of N fertilisers, shifts to perennial polyculture cropping systems, no till practises in grasslands (Wattiaux et al., 2019).

Ruminants are estimated to transform ~2.7 billion tons of grass DM into nutritious proteins and do not compete with humans for grass, crop residues and industry by-products (Dijkstra et al., 2013; Mottet et al.,2017). When efficiency is expressed in terms of human inedible protein conversion, ruminants perform better than non-ruminants (Reynolds et al., 2011). Milk production achieves comparatively better feed conversion ratios when human edible diet proportions are considered, and when nutrient density is factored into climate impact milk performs comparatively better than orange juice and soya-based drinks (Smedman et al., 2010; Wilkinson, 2011). Conversely, Poore et al. (2018) found impacts from soya milk to be less than cows' milk for GHGs, land use, EP and AP when using consolidated meta data, however nutritional benefits and the role of ruminants in grassland ecosystems, were not accounted for. Choice of appropriate functional unit can easily affect perceived performance and comparison with other foodstuffs and an assessment using indices expressing non-human edible protein conversion could be a worthwhile additional comparison of the dairy systems.

An increased human population in both size and wealth demand protein rich diets and the absolute number of livestock continues to increase (IPCC, 2019). Milks provide nourishment for humans in an ‘energy dense’ form that delivers high value protein and micronutrients (FAO, 2011), and milk also provides all essential amino acids which is a property not present in vegetable proteins (Dijkstra et al., 2013). The environmental burden of milk production should be reduced, and more circular methods of farming adopted, as agriculture has a part to play in national emissions reductions.

Low meat-eating and vegetarian UK diets are estimated to emit 4.7 and 3.8 kg CO_2e/ day, or 1.7 and 1.4 tonnes CO_2 per person per year. These emissions will be able to be reduced in future through on farm mitigation measures, however national emissions reduction strategies should be tackled in an equitable manner. Should a UK resident decide to take a weekend shopping trip to New York, their aviation emissions including uplift would total 1.0 tonnes in economy class or 2.1 tonnes in premium seat classes. It is not justifiable to impose stringent environmental legislation on agriculture, land use and food production if progress to reduce national emission is undone by other behaviours. It may be more equitable to allot UK citizens individual carbon credits for non-essential carbon intensive goods and services. Using aviation as an example, citizens that are frequent flyers who exceed their annual allotted carbon credit and would need to secure additional carbon credits from citizens who lead a lower carbon lifestyle. In addition, policies could be developed to discourage unnecessary carbon intensive behaviours where possible, for example short-haul flights could be replaced by rail travel where possible.

7.1.3 Future work

This research does not represent a complete range of dairy regimes found in the UK and the results raise a question as to whether greater profitability and or lower environmental impact or resource use could have been achieved by high producing merit cows in systems with very low concentrate input and a focus on grazing. Even though Holstein Friesian is the most common breed found on UK dairy farms (March et al., 2014), other breeds of cow such as Ayrshire or crossbreeds have not been considered in this study. The inclusion of dairy beef management regimes would also be of interest when comparing indicators across farming systems.

This research does not incorporate an exhaustive list of possible indicators associated with dairy farming such as biodiversity, animal welfare and water use because data was not available for all the systems or was not able to be gathered retrospectively. The United Nations (2019) report that biodiversity within ecosystems, and within and between species, is declining at a higher rate than previously seen mainly due to anthropogenic effects that include land use change and climate change. Humanity relies on nature to supply air, fresh water, soil, to regulate the climate, to control pests and sustain animals that pollinate over 75% of food crop types globally (Diaz et al., 2019). Species impacts include changes in the distributions, phenology (cyclic and seasonal effects), population dynamics and communities (Diaz et al., 2019). Agricultural policies should be developed to preserve ecosystem services and one example of how dairy systems could be altered was shown by Cole et al. (2019) who applied nutritional models to alter overall land use and requirements so as to increase spare land or biodiversity rich grasslands.

Other than the health indicators of BCS and LCS, no quantifications of animal behaviour or welfare were included in this research. Accelerometer data is available for the current dairy systems and proxies such as lying time may be an appropriate measure to use for Langhill cows. Criteria to assess animal welfare can focus on animal health and wellbeing, rearing system and five freedoms. Animals should be able to express normal behaviour, have access to food, water, shelter, and veterinary treatment, and should not be in a state of fear. Indicators of wellbeing include areas available for cows to feed, drink and rest, and animal health measures include dry cow and calf management, udder health and prevalence of lameness (IDF, 2018b). Further indicators such as antibiotic use and associated milk losses and wastes is also an area of the food supply chain of current interest and one which could have been modelled across the dairy systems.

Water is a valuable resource, essential on dairy farms for animals, for washing and for growing crops and measures should be implemented to audit and reduce water use and waste where possible in order to increase efficiency and save costs. Water use is measured by categorising types, Blue indicates direct use of potable water, Green refers to rainwater, and grey to a wastewater that is able to be reused. A survey of Promar dairy farms in the UK found livestock drinking represented up to 50% of direct water usage and that mains water supply averaged £41 /cow/year (AHDB, 2015). An estimate of Blue and Green water requirements would be a relevant additional indicator.

The Langhill herd currently represents the world’s longest running breeding and feeding experiment and a wide range of industry questions have been answered using the data which is a valuable resource. Future trials could continue to focus on a merit selected for milk, fat and protein because this would not interfere with the history of the Langhill herd and longevity of the experiment, however the current average merit comparison could be bred for herd robustness by selecting for management traits such as fertility and feed conversion efficiency or by using novel breeding techniques. Perhaps using the petal diagrams in Chapter 6 could be used as a basis for improving multiple environmental indicators areas of overall improvement in a similar way in a similar way to the use of multi-trait selection indexes in animal breeding. The petal diagrams could be extended to include further indicators types, finer detail, or targets such as levels of GHG emissions. Feeding trials could vary, perhaps tailored to lowest GHGs, some with a focus on maximum yield for lowest emissions or with crop rotations could be introduced that focus on both soil and animal. Grassland is an abundant resource in many dairying areas and more could be done to understand animal health and soil benefits of no till, polycultures and perennials. Further work could be done to explore dairy system outcomes stemming from actual mitigation of GHG emissions. AgRECalc could be improved by further modelling of sequestration and enabling some mitigation measures to be accounted for so that farm mitigation measures could be represented. Alternative methods of accounting for methane could be explored with a view to aiming for stabilised UK livestock methane emissions.

The UK MDSM could be improved by including a wider range of on-farm crops within the model. The current UK MDSM could be applied to answer pertinent industry questions and generating scenarios of interest, such as questions related to improvements of forage, for example the economic effects of improving silage quality (through increased metabolisable energy). Further work could be done to link the UK MDSM to AgRECalc so that carbon footprints could be generated to estimate the environmental benefits or consequences of scenarios that examine financial improvements. Work could be done to broaden the Polar Charts by considering methods other than equal weighting. Weighting individual indicators and expressing uncertainty or environmental goals within the petal diagrams could be a further development. The diagrams may be limited by multiple indicators and in that case multiple polar charts could be used.

Data availability was not an issue in this study. However, comparability of impacts stemming from agricultural LCA’s continues to cause problems due to variations in study scope, boundary and use of emission factors for feed components, energy use. International methods have been agreed for footprinting using IPCC methodology and these should extend to other environmental impacts that can influence GHG emissions for example acidification potential. Emission factors available for feed components vary between countries and sources and should be standardised perhaps into a tier system available as a dynamic open resource for each country.

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9 Appendix