Effects of changing cow production and fitness traits on profit and greenhouse gas emissions from UK dairy systems

Short title: *Biological traits and emissions from UK dairying*

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SUMMARY

The aim of this study was to compare the effect of changing a range of biological traits on farm profit and greenhouse gas emissions (expressed as carbon dioxide equivalent, CO_2-eq.) in the UK dairy cow population. A Markov chain approach was used to describe the steady-state herd structure of the average milk-recorded UK dairy herd, as well as to estimate the CO_2-eq. emissions per cow, and per kilogram of milk solids (MS). Effects of changing each herd production and fitness trait by one unit (e.g. 1 kg milk; 1% mastitis incidence) were assessed, with derived values for change in profit (economic values) being used in a multi-trait selection index. Of the traits studied, an increase in survival, and reductions in milk volume, live weight, residual feed intake, somatic cell count, mastitis incidence, lameness incidence and calving interval were traits that would be both profitable, and reduce CO_2-eq. emissions per cow and per kg MS of a dairy herd. A multi-trait selection index was used to estimate the annual response in production and fitness traits and the economic response, with an estimate of annual profit per cow from selection on multiple traits. Milk volume, milk fat and protein yield, live weight, survival and dry matter intake were estimated to increase each year and body condition score, residual feed intake, somatic cell count, mastitis incidence, lameness incidence and calving interval were estimated to decrease, with selection on these traits estimated to result in an annual increase of 1% per year in GHG emissions per cow, but a reduction of 0.9% per unit product. Improved efficiencies of production associated with a reduction in milk volume (and increasing fat and protein content), live weight and feed intake (gross and metabolic efficiency respectively), and increase in health, fertility and overall survival will increase farm annual profit of UK dairy systems and reduce their environmental impact.

INTRODUCTION

Given the effect of greenhouse gas (GHG) emissions on climate change, mitigation of methane (CH_4) and nitrous oxide (N_2O) emissions from dairy systems has gained importance in recent years. Bell *et al.* (2013a) adapted and developed an existing dairy Breeding Objectives Model, a dynamic model used to calculate economic values for breeding objectives, to include nutrient partitioning to allow investigation of GHG abatement options over a cow’s lifetime. Tools such as this are needed by the dairy industry to make informed changes that are economically viable and environmentally sustainable. The losses of dietary energy in the form of CH_4, as well as nitrogen in manure, are significant inefficiencies associated with dairy production and sources of pollution (FAO, 2010).

In the UK, the traditional dairy system is for cows to graze pasture during the summer months, with conserved forage and concentrate feed as supplements in summer and sole ration components in winter, to achieve the genetic potential of the cow for milk production. Although GHG emissions from dairy systems account for less than 2% of the UK's total annual GHG emissions (UKGGI, 2010), improvements in efficiency of milk production, which can be made immediately through feeding and management changes or in the medium to long-term by breeding, are considered an effective means of minimising the environmental impact and increasing profitability of dairy systems (Bell *et al.* 2012). Breeding is a cost effective means of abating emissions in the medium to long-term (Moran *et al.* 2007).

Although heritabilities of fitness (health and fertility) traits can be low compared to production traits, the large coefficient of genetic variation for traits such as mastitis (33%) and lameness (45%) suggests there is considerable potential for genetic improvement (Pritchard *et al.* 2012). Pritchard *et al.* (2012) found the coefficient of genetic variation in the recorded UK dairy population to range from 11 to 13% for moderately heritable milk production traits, but to be as low as 3% for somatic cell count (SCC) and calving interval. Bell *et al.* (2013a) showed that improved efficiencies of production associated with health and fertility (and overall survival), as well as feed efficiency, could reduce GHG emissions from Australian dairy herds. In the UK, Bell *et al.* (2011) modelled an experimental herd to assess the effect of changing a range of biological traits but the experimental design limited full expression of survival, and possibly health and fertility incidences as well. The current study used a more comprehensive modelling approach to assess variation in biological traits, including fitness and feed efficiency traits, in the UK national dairy population.

The objectives of the present study were: (1) to model changes in profit and GHG emissions in response to changes in biological traits for the average milk-recorded dairy herd in the UK, (2) to assess the effect of a unit change in a range of production and fitness traits on profit per cow, GHG emissions per cow and per kg milk solids (MS) for the average dairy herd, and (3) to assess the annual economic responses to selection and reduction in emissions per cow and per kg MS from selection on multiple traits.

MATERIALS AND METHODS

Data

A model used in Australia to calculate economic values for dairy breeding objectives (Visscher *et al*. 1994; Pryce *et al*. 2009) was adapted and developed by Bell *et al.* (2013a) to model GHG emissions from a dairy herd. For a full description of the Breeding Objectives Model see Bell *et al.* (2013a). Briefly, the model was constructed in Microsoft Excel to calculate changes in profit per cow in response to changes in biological traits. For the current study, the model was extended to include changes in GHG emissions per cow and per kg MS due to a management or genetic change. Responses were quantified by calculating differences between the current state (baseline situation) and a positive or negative change in a biological trait (adjusted situation). The extended model was used in the current study to dynamically represent the average milk-recorded UK dairy herd (referred to as the average herd) and to assess effects of changes in biological traits.

Herd structure

A total of 13 age groups were modelled, which included the period between birth and first calving for herd replacements, and 12 lactations. Replacement animals were assumed to calve at 2 years of age, with cows surviving for an average of 2.9 lactations which is in accordance with recent UK estimates (Table 1). It was assumed that all births resulted in a single live calf, and that 50% of calves were male and 50% female. The only animals to leave the system were cull cows, male calves and surplus female calves. All calves sold were assumed to leave the system immediately after birth (and contribute no GHG emissions to the system). This assumption ignores the effect of calf mortality, which was assumed to be the same in both the baseline and altered situations.

Herd structure was derived using a Markov chain approach. A Markov chain can be used to describe the herd as a vector of states (s) that cows occupy at a given point in time (Stott *et al*. 1999), which in this study was each age group. The vector of states at time t is multiplied by a matrix of transition probabilities (s × s) to give the vector of states at time t + 1. The probability of a cow progressing to the next lactation (from lactation *n* to *n* + 1 and from lactation 1 to *n*) was dependent on the chance of a cow being culled during the current lactation (Table 2). If the transition matrix is constant for all stages; that is, the model is stationary, then repeated matrix multiplication will produce a fixed long-run vector (steady-state), which is independent of the initial state vector. This long-run steady-state vector provides a useful basis for comparative assessment of alternative herd structures i.e. a change in the number of cows in each age group, as shown in Table 2. The number of replacements required to maintain the average herd structure was 34.4 animals per lactation in a 100 cow herd. For simplicity individual cow values were multiplied by 100 to represent a herd of 100 cows.

Energy requirements, feed intake and live weight

It was assumed that energy requirements (of milking cows and herd replacements) for maintenance, growth, pregnancy, activity and lactation were achieved and that feed intake was always sufficient to achieve energy requirements in the baseline situation.

The diet composition of a lactating cow was calculated based on the average animal (Table 1) using the FeedByte® rationing model version 3.78 (available at http://www.sruc.ac.uk/info/120110/dairy/354/dairy_services-key_features), which calculates a least cost ration that meets the energy, protein and mineral requirements of the animal. The ration was formulated from pasture, grass silage and dairy concentrate based on their nutrient composition (Table 3) and cost (Table 4). The diet was constrained to a maximum of 500 g pasture per kilogram of fresh feed. The lactating cow diet consisted of 340 g pasture, 320 g grass silage and 340 g dairy concentrate per kilogram DM intake per lactation (Table 3), at an estimated cost of 8.6 pence per litre of milk. This diet was considered representative of a typical UK feeding system (Wilkinson & Audsley, 2013). A milking herd replacement (growing heifer) was assumed to be fed a diet of 500 g pasture and 500 g grass silage per kilogram of fresh feed. The cost of feed consumed by each age group was estimated by multiplying total DM intake by ME content and cost per unit ME of the diet (Table 4). A unit reduction in DM intake assumed that ME requirement of the animal remained constant in the baseline and adjusted situations, but ME intake and associated cost of consumed feed were lower to represent an improvement in residual feed intake.

Metabolisable energy (ME, MJ/d) required for maintenance (E_{maint}), gain or loss of body protein (E_p) and lipid (E_l), pregnancy (E_{preg}), activity (E_{act}) and lactation (E_{lact}) for the average cow are presented in Table 5. The effective energy system proposed by Emmans (1994) was used to estimate feed intake. Feed intake of an animal was calculated from total ME requirement and the net energy supplied by the food consumed:

Feed intake (kg DM/d) = $E_{total} \times 1/(ME - 0.616 \times (E_{CH4} \times GE) - (3.8/20 \times (FE \times GE)) - 29.2 \times (DCP/6.25))$

where ME, GE, FE and E_{CH4} is the metabolisable, gross, faecal and enteric CH_4 energy (all MJ/kg DM). The values of 0.616 and 3.8 are the heat increments associated with fermentation and faeces production, and energy lost in faeces was assumed to be 20 MJ/kg faeces DM. Excretion of urine leads to a loss of digestible crude protein (DCP) (Emmans, 1994). Residual feed intake is defined as the difference between actual and predicted feed intake. Residual feed intake represents variation in efficiency of metabolic processes, which is independent of the animal's body size and production level; which for example, can be estimated from regression of DM intake against mean body weight and growth rate in heifers (Williams *et al.* 2011). The economic value for RFI is the cost of increasing marginal feed costs by one unit while all other traits are held constant. So, even if feed intake is sufficient, an animal that eats less will be more profitable at the same level of milk production and fitness.

The animal's live weight was assumed to be its empty body weight (kg of protein, lipid, water and ash) plus gut fill. Figure 1 shows the live weight and body composition of the average cow assumed in this study with a mature empty body weight of 550 kg. The body condition score of the cow was estimated from body lipid using the equation of Wright (1982) and converted to a 1 to 9 point scale (NRC, 2001) for this study using the following formula:

Body condition score (1 to 9 scale) = ((Body lipid % × 0.12 + 0.36) – 1) × 2 + 1

The average live weight of a cow was estimated to be 632 kg, with a body condition score of 4.5 on a 9 point scale (Table 6). Gut fill was assumed to equate to the water held by dietary fibre content and estimated as 13.2 times the intake of NDF (kg/d) (Takeda and Kiriyama, 1978).

Calculation of yields per cow lactation

Data for average number of days for each lactation, milk production at maturity and milk composition were obtained for the year 2011/12 from the Centre for Dairy Information (CDI, 2013), which collates data from recorded dairy cows in all regions of the UK (Table 1).

The total amount of milk produced during each lactation was estimated by multiplying the milk production at maturity from the CDI data by the proportion of mature productivity for each lactation. The proportion of mature productivity was calculated to be E_{maint} - (E_p + E_l)/maximum of E_{maint} - (E_p + E_l) across lactations (Bell *et al.* 2013). Mature productivity of milk was reached at 4 lactations for the average cow (CDI, 2013). Amounts of milk protein, fat and lactose produced were calculated based on milk fat and protein content (Table 1), and an assumed milk content of 5% lactose. Average yields per lactation were 8,965 litres of milk, 358 kg of fat and 290 kg of protein (Table 6).

Greenhouse gas emissions

Sources of greenhouse gas emissions were from enteric and manure CH_4 and direct (from stored manure and application of dung, urine and manure) and indirect N_2O from storage and application of manure to land (from leaching and atmospheric deposition of nitrogen from NOx and NH_3) as attributed in the UK National GHG Inventory for agricultural production (UKGGI, 2010). Emissions were expressed as CO_2-eq. emissions per cow, and per kilogram of MS; the functional units as defined by Guinée *et al.* (2002). Kilograms of CO_2-eq. emissions for a 100-yr time horizon were calculated using conversion factors from CH_4 to CO_2-eq of 25 and from N_2O to CO_2-eq of 298 (IPCC, 2007).

Enteric CH_4 emissions were estimated per kg DM intake by the equation (Bell *et al.* 2013b) based on the composition of the diet (Table 3) as:

$$CH_4 \text{ (g/kg DM intake)} = 0.05642 \times DOMD_p - 0.1986 \times EE - 0.009214 \times NFC - 2.698 \times (1000/[1000 - DOMD_m]$$

where $DOMD_p$, $DOMD_m$, and are digestible organic matter at the production and maintenance intake levels, EE is ether extract, and NFC non-fibre carbohydrate (all g/kg

DM). The $DOMD_p$ and $DOMD_m$ contents were estimated from the organic matter concentration of the diet (g/kg DM) multiplied by digestibility of organic matter at the production (OMD_p) and maintenance intake level (OMD_m). The OMD_p was estimated by the equation of Huhtanen *et al.* (2009) as:

OMD_p (% of OM) = 257 + 6.85 × OMD_m - 2.6 × DM intake (kg/day)/10

where OMD_m (% of OM) is the digestibility of organic matter at the maintenance intake level. The CH_4 emissions per kg DM intake were converted to emissions as a % of feed GE in the model, which meant CH_4 emissions were about 6.8% of GE for the pasture/silage diet fed to a herd replacement and 5.6% of GE for the pasture/silage/concentrate diet of a lactating cow. This corresponds well with the loss of CH_4 per % of feed GE of 6.5 ± 1% proposed by IPCC (2006) for high to low forage diets for dairy cows and UK GHG inventory values (UKGGI, 2010). Estimated annual emissions (from Table 6) for CH_4 (144 kg/yr for enteric and 42 kg/yr for manure) and N_2O (8 kg/yr) were higher than in the UK GHG inventory. Data in the current study were from recorded cows, which are typically selected for improved production. Losses of CH_4 and N_2O emissions were estimated by using linear relationships for all biological traits except survival (a curvilinear relationship with survival is generated by the Markov chain).

IPCC (2006) Tier II methodology was used to predict manure CH_4 and N_2O emissions (from N excretion) for manure handling systems, as well as manure deposited on pasture. The N excreted by the animal was partitioned into dung (N intake – digested N intake) and urine (N intake – (N retained + N in dung)). Emission factors for manure CH_4 and N_2O are shown in Table 7. Based on UK GHG inventory values the following were fixed in the calculations: CH_4 conversion factor of 0.662 $m^3\ kg^{-1}$ CH_4 and CH_4 producing capacity of manure of 0.24 $m^3\ kg^{-1}$ volatile solids (UKGGI, 2010). Volatile solids in manure were calculated from the undigested organic matter (1 – digestible organic matter kg/kg).

Fertility

All cows were assumed to be artificially inseminated. The average number of inseminations per cow was calculated as:

No. of inseminations = 1 + ((calving interval (days) – (gestation length (days) + start of oestrus (days)))/21)

where the start of an oestrous cycle was assumed to be 426 days after birth for a replacement heifer and 82 days after calving for a lactating cow. Gestation length was assumed to be constant at 283 days (Table 1). This allows for a replacement to enter the herd at 730 days of age and a milking cow to have a 365 day calving interval. Calving interval was determined from the average lactation length plus the drying off period (Table 2). The cost of poor fertility was calculated from the cost of each insemination (labour cost per hr/2 + semen straw cost; Table 4), the additional feed consumed by a milking cow and the cost of a milking herd replacement per extra day required.

Mastitis and lameness

Along with poor fertility, mastitis and lameness are considered to be two of the most costly health problems in dairy cattle and are therefore included in the model. The percentage of cows in each lactation that had mastitis (Table 2) was calculated using a cumulative normal distribution with a mean log transformed SCC of 400,000 somatic cells/ml (de Haas *et al.* 2004). A linear extrapolation of the data of Rutherford *et al.* (2009) provided the increase in incidence of lameness with parity (Table 2). A cow with mastitis and lameness had an associated cost for treatment and loss of milk (Appendix). For mastitis, 0.3 incidences were assumed to be clinical cases; for lameness, 0.25 were assumed to be clinical cases; the remainder were assumed to be subclinical cases. A case of clinical mastitis was assumed to cost £206 per incidence and subclinical £54, which is consistent with costs reported by Heikkilä *et al.* (2012). A case of clinical lameness was assumed to cost £305 per incidence and subclinical £40, which is consistent with costs reported by Willshire & Bell (2009). The cost of mastitis and lameness are shown in the appendix (Table A).

Change in profit

The model included a partial budget calculation to determine the change in profit (e.g. income – variable costs = profit or loss) per cow for each age group in the herd for a change in a trait; this is often referred to as the economic value of the trait. The change in income corresponds to the maximum amount of money that could be made by a change of one unit in each trait (e.g. 1 kg milk or 1% mastitis incidence). Economic value of a trait is over a lifetime, but breeding values are expressed in lactating cows, so feed costs of growing heifers and lactating cows are shared amongst lactating cows. Variable costs and income that correspond to the traits of interest were included in the analysis in pounds sterling (Table 4). The average values for milk, feed and livestock prices were obtained from Redman (2012).

Improved efficiencies of production

The change in profit, CO_2-eq. emissions per cow and per kg MS by a single unit change in each of 11 biological traits was assessed. The 11 traits represent a range of production traits and fitness traits. An increment of one unit increase in each trait was investigated while keeping all other traits constant. The traits assessed were: production traits of milk volume (litres/lactation), fat and protein yield (both kg/lactation), live weight (kg), body condition score (1 to 9 point scale), survival (%/lactation), and feed efficiency and fitness traits of residual feed intake (kg/day), SCC ('000 cells/ml), mastitis and lameness incidence (both %/lactation) and calving interval (days/lactation). The average value and unit for each trait per cow assumed in the modelled average herd is shown in Table 6.

A multi-trait selection index, as described by Pryce *et al*. (2009) and Hayes *et al.* (2011), was used to estimate the annual change in the 11 traits and the economic change, with an estimate of annual change in profit per cow from selection on multiple traits. A multi-trait selection index takes into account the economic values of the traits included, their heritabilities, and genetic and phenotypic correlations between traits in order to calculate optimal index weights for each trait (Pryce *et al*. 2009). Phenotypic and genetic correlations between traits were mostly obtained from Pritchard *et al.* (2012), except for live weight, condition score (both Pryce *et al*. 2009), and DM intake and residual feed intake (Veerkamp *et al.* 1995; Vallimont *et al.* 2010 and 2013). Economic values were derived using the Breeding Objectives Model described earlier.

RESULTS

Change in profit

A 1 kg increase in residual feed intake resulted in the largest change in profit compared to the baseline situation of £-52.23 per cow (Table 8). Other notable changes in profit were an increase of £9.59 per cow for a 1% increase in survival and an increase of £3.90 per cow for an increase of 1 kg per lactation in milk protein yield.

Efficiencies of production and greenhouse gas emissions

The largest contribution to total CO_2-eq. emissions came from enteric fermentation (0.51), followed by N_2O (0.34) and CH_4 from manure (0.15) (Table 6).

Of the 11 traits studied, a 1 kg increase in residual feed intake produced the largest change in CO_2-eq. emissions of 662 kg per cow and 1026 g per kg MS over the lifetime of a cow (Table 8). A 1 unit increase in most traits resulted in an increase in emissions per cow and per kg MS, but an increase in survival reduced emissions per cow and per kg MS, and an increase in milk fat and protein yield reduced emissions per kg MS. Traits where a single unit change (increase or reduction) would result in both a desirable increase in profit and a reduction in emissions intensity per cow and per kg MS were an increase in survival and decreases in milk volume, live weight, residual feed intake, SCC, mastitis incidence, lameness incidence and calving interval.

Responses to selection

In practical situations, selection is often on several traits simultaneously, rather than single-trait selection. Selection on multiple traits using a multi-trait selection index where each trait is weighted by its respective optimal index weight (Table 9) showed that profit is expected to increase by £29.02 per cow per year, largely through increased milk fat and protein yields, and survival. Inserting the predicted annual response of each trait in Table 9 into the Breeding Objectives Model showed that CO_2-eq. emissions are estimated to increase by 1.0% per cow and to decrease by 0.94% per kg MS per year based on the estimated annual response.

DISCUSSION

Production efficiency can be defined as milk or milk solids output per unit of total feed input over an animal’s lifetime, including the rearing phase. Production efficiency is directly related to profit because milk revenue and feed costs are the major economic drivers in dairying. Of the production traits studied, increases in milk fat and protein yields were associated with increased profit, whereas increases in live weight and body condition score were associated with reduced profit. These responses are expected because milk fat and protein yields represent direct income; live weight and body condition score represent indirect costs through energy requirements and feed intake. Increased milk volume yield might also be expected to increase profit, but the model assumed a charge on milk volume (e.g. penalty for exceeding milk production quota or supply contract), so an increase in milk volume, while keeping all other traits studied constant, was associated with reduced profit. Residual feed intake is a trait derived from production traits and feed intake, so is directly related to profit; the relationship is negative, however, because animals with lower RFI are more efficient (Williams *et al.* 2011).

Increases in all of the health and fertility traits (SCC, mastitis and lameness incidence, and calving interval) were associated with reduced profit because these traits represent direct costs through veterinary treatment, and indirect costs through lower milk production and higher culling rates. Culling rate inversely determines survival, which was positively associated with profit because cows that survive longer in the herd have higher average annual milk yield and have fewer associated heifer replacements (Garnsworthy, 2004).

In general, production traits were positively related to GHG emissions per cow because of the positive relationships of milk yield and live weight with feed intake, which is the main driver of GHG emissions. Increased milk solids yield reduced GHG emissions per kg milk solids as expected from the calculation. Similarly, fitter cows produce more milk, so improvements in fitness traits reduced GHG emissions per cow and per kg milk solids. For survival, however, the relationship was negative because cows that survive longer spread GHG emissions accumulated during the rearing phase over more total output of milk solids (Garnsworthy, 2004).

Economic values of traits

Generally, the economic values calculated in this study (Table 9) were similar to those currently implemented in UK genetic evaluations (Wall *et al.* 2010a) for the health and fertility traits (allowing for the difference in how lifespan and survival traits are derived), but values for milk fat and protein yields were higher in the current study. Higher economic values will increase the estimated annual economic response for each trait. Economic values for live weight, condition score and feed efficiency are not included in the UK selection index, so economic values for these traits are new. Although assumptions are used (along with actual national records) to model a cow over its lifetime to derive economic values, Pryce *et al.* (2009) showed that economic values derived using the Breeding Objectives Model are generally robust to these assumptions. The annual response to selection was more sensitive to the price of milk compared to other assumed production values. A 20% change in milk fat and protein price would change estimated profit per year by 28%; a 20% change in cost of feed (£/MJ; Table 4) by 8%; and a 20% change in milk production (Table 1) by 1%. Ultimately, the best assumptions available have to be used to complement actual records in order to calculate economic values and responses to selection.

The fertility trait evaluated was calving interval. The only information required to calculate calving interval are calving dates, which makes it an easy measure of fertility to evaluate, although calving interval is censored as it requires a subsequent calving, so cows culled for infertility are not present. In the UK, the current genetic evaluation of fertility is an index that includes calving interval and non-return rate 56 days after insemination (Pritchard *et al.* 2012). The cost of each day over the optimal calving interval length, which is easily estimated, is associated with poor fertility. Poor fertility also increases the number of herd replacements required and can contribute up to 20% of GHG emissions by a herd (Garnsworthy, 2004).

Selection on efficiency traits and greenhouse gas emissions

Some improvement in gross efficiency of dairy systems has been achieved already though selection on production (Veerkamp, 1998) and greater improvement could potentially be made through selection on metabolic efficiency e.g. residual feed intake (Veerkamp *et al.* 1995). . In the current study selection for residual feed intake was profitable and as a single trait was found to reduce GHG emissions per cow and per unit product more than other traits studied. In contrast to a study by Bell *et al.* (2011) on dairy cows in the UK, the current study found that a unit decrease in calving interval, SCC, mastitis incidence and lameness incidence would also bring profitable net reductions in GHG emissions per cow and per kg MS.

The main benefits of selection to improve production efficiencies are through increased productivity and gross efficiency (i.e. the ratio of yield of milk to resource input) by firstly, diluting the maintenance cost of animals in the system and secondly, less animals are required to produce the same amount of product (Garnsworthy, 2004; Capper *et al.* 2009; Wall *et al.* 2010b). Studies have found that more energy efficient animals produce less waste in the form of CH_4 and nitrogen excretion per unit product (van de Haar and St Pierre, 2006; Chagunda *et al.* 2009). Jones *et al.* (2008) calculated that in the last 20 years genetic improvement in dairy cows in the UK from selecting on economic and production efficiency had reduced GHG emissions per unit product by 0.8% per year and would continue to reduce emissions at a rate of 0.5% per year over the next 15 years. A reduction of 0.6% per year in GHG emissions per unit product was found in the US over a 63-year period (Capper *et al.* 2009). In a UK experimental herd, Bell *et al.* (2010) calculated that enteric CH_4 emissions per unit product had decreased by 1.1% per year for cows selected for many generations on increased milk fat and protein production and had decreased at 1.4% per year for cows selected to represent the UK average for milk fat and protein production. Based on the annual genetic response in each trait, the current study predicted a reduction in GHG emissions per unit product of 0.9% per year, but GHG emissions per cow were estimated to increase by 1.0%. Increasing the genetic potential of a cow to produce milk increased GHG emissions per cow due to a higher feed intake, but selection on body maintenance requirements (e.g. live weight as an approximation for maintenance) or feed efficiency could help reduce emissions per cow and per unit product.

In the medium to long-term, selection will make permanent and cumulative gains in fitness traits such as survival and fertility, but management effects can be implemented in the short to medium term. The reduction in emissions per cow and per unit product associated with mastitis and lameness incidence are partially accounted for by phenotypic and genetic variations in survival (for both health traits) and calving interval (assumed to be longer for lame cows). The contribution of improving survival, feed utilisation and fertility to reducing GHG emissions intensity of dairy systems in the UK is similar to that seen in Australia (Bell *et al.* 2013a).

Given the low heritability of fitness traits such as fertility, survival, mastitis and lameness, reductions in emissions intensity of dairy systems may be harder to achieve than selection on a production trait such as feed intake or residual feed intake (i.e. feed efficiency). Customised selection indices, where producers create index weights specific to their farm circumstances, would be possible using the Breeding Objectives Model. As suggested by others (Cottle and Coffey, 2013), customised selection indices are appropriate for fitness traits with low heritability and, given their association, with reductions in GHG emissions intensity. Using a multi-trait selection index with the economic values derived in this study (Table 9), the annual increase in profit from selection would be £29.02 per cow. This is higher than previously reported (£7.11, Wall *et al.* 2010a), but derives from use of higher economic values for milk production traits due to an increase in average price of milk from 17 pence per litre in previous calculations (Stott *et al.* 2005) to 24 pence per litre in the current study, and the use of recently published phenotypic and genetic parameters for the UK (Pritchard *et al.* 2012).

Selection on feed efficiency or CH_4 output is not yet available in the UK, but using DNA information is especially promising for difficult or expensive to measure traits such as these (de Haas *et al.* 2011). Routine measurement of feed intake is costly, but genomic selection on feed intake and feed efficiency is possible (Hayes *et al.* 2011; de Haas *et al.* 2012). It may also be found that residual feed intake explains sufficient variation to be a proxy for enteric CH_4. However, although proxies for CH_4 emissions and nitrogen efficiency, such as measures of feed efficiency, can explain a large proportion of phenotypic variation (de Haas *et al.* 2011), in the case of enteric CH_4, direct measurement is cheaper, quicker and simpler, and revealed considerable genetic variation among animals (Garnsworthy *et al.* 2012). It was assumed that the biological traits assessed explained the majority of variation in enteric CH_4 emissions and nitrogen efficiency.

CONCLUSIONS

This study showed that increased production efficiencies associated with an increase in survival, and decreases in milk volume (increasing fat and protein content), live weight, feed efficiency, SCC, mastitis incidence, lameness incidence and calving interval, would increase profit and reduce emissions per cow and per kg MS of dairy systems. The GHG emissions per cow are estimated to increase by 1% per year and reduce by 0.9% per unit product based on current breeding objectives and the inclusion of residual feed intake. Predicted improvements in health and fertility (and overall survival), and residual feed intake will increase farm annual profitability and reduce GHG emissions.

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REFERENCES

BANOS, G., COFFEY, M. P., WALL, E. & BROTHERSTONE, S. (2006). Genetic relationship between first-lactation body energy and later-life udder health in dairy cattle. *Journal of Dairy Science* **89**, 2222-2232.

BARKER, Z. E. (2007). *Epidemiology of lameness in dairy cows*. PhD Dissertation. The University of Warwick.

BELL, M. J., WALL, E., RUSSELL, G. & SIMM, G. (2010). Effect of breeding for milk yield, diet, and management on enteric methane emissions from dairy cows. *Animal Production Science* **50**, 817-826.

BELL, M., WALL, E., RUSSELL, G., SIMM, G. & STOTT, A. (2011). The effect of improving cow productivity, fertility, and longevity on the global warming potential of dairy systems. *Journal of Dairy Science* **94**, 3662-3678.

BELL, M. J., ECKARD, R. J. & PRYCE, J. E. (2012). Breeding dairy cows to reduce greenhouse gas emissions. In Livestock Production (Ed. K. Javed), pp.47-58. InTech Publishing, Croatia.

BELL, M. J., ECKARD, R. J., HAILE-MARIAM, M. & PRYCE, J. E. (2013a). The effect of changing cow production and fitness traits on net income and greenhouse gas emissions from Australian dairy systems. *Journal of Dairy Science* **96**, 1-14.

BELL, M. J., ECKARD, R. J., CRAIGON, J., MOATE, P. J. & GARNSWORTHY, P. C. (2013b). Modelling the effect of diet chemical composition on enteric methane emissions. In: *Proceedings of the Greenhouse Gases in Animal Agriculture conference, Advances in*

Animal Biosciences **4**, 441.

Capper, J. L, Cady, R. A. & Bauman, D. E. (2009). The environmental impact of dairy production: 1944 compared with 2007. *Journal of Animal Science* **87**, 2160-2167.

Centre for Dairy Information (CDI) (2013). http://ukcows.com/thecdi. Accessed February 21, 2013.

Chagunda, M. G. G, Römer, D. A. M. & Roberts, D. J. (2009). Effect of genotype and feeding regime on enteric methane, non-milk nitrogen and performance of dairy cows during the winter feeding period. *Livestock Science* **122**, 323-332.

Cottle, D. J. & Coffey, M. P. (2013). The sensitivity of predicted financial and genetic gains in Holsteins to changes in the economic value of traits. *Journal of Animal Breeding and Genetics* **130**, 41-54.

de Haas, Y., Windig, J. J., Calus, M. P. L., Dijkstra, J., de Haan, M., Bannink, A. & Veerkamp, R. F. (2011). Genetic parameters for predicted methane production and the potential for reducing enteric emissions through genomic selection. *Journal of Dairy Science* **94**, 6122-6134.

de Haas, Y., Calus, M. P. L., Veerkamp, R. F., Wall, E., Coffey, M. P., Daetwyler, H. D., Hayes, B. J. & Pryce, J. E. (2012). Improved accuracy of genomic prediction for dry matter intake of dairy cattle from combined European and Australian data sets. *Journal of Dairy Science* **95**, 6103-6112.

de Haas, Y., Veerkamp, R. F., Barkema, H. W., Gröhn, Y. T. & Schukken, Y. H. (2004). Associations between pathogen-specific cases of clinical mastitis and somatic cell count patterns. *Journal of Dairy Science* **87**, 95-105

Emmans, G. C. (1994). Effective energy: A concept of energy utilisation applied across species. *British Journal of Nutrition* **71**, 801–821.

Food and Agriculture Organization of the United Nations (FAO) (2010).

Greenhouse Gas Emissions from the Dairy Sector - A Life Cycle Assessment. Rome: Food and Agriculture Organisation.

GARNSWORTHY, P. C. (2004). The environmental impact of fertility in dairy cows: A modelling approach to predict methane and ammonia emissions. *Animal Feed Science and Technology* **112**, 211–223.

GARNSWORTHY, P. C., CRAIGON, J., HERNANDEZ-MEDRANO, J. H. & SAUNDERS, N. (2012). Variation among individual dairy cows in methane measurements made on farm during milking. *Journal of Dairy Science* **95**, 3181-3189.

GUINÉE, J. B., GORREE, M., HEIJUNGS, R., HUPPES, G., KLEIJN, R., DE KONING, A., VAN OERS, L., WEGENER SLEESWIJK, A., SUH, S., UDO DE HAES, H. A., DE BRUIJN, H., VAN DUIN, R., HUIJBREGTS, M. A. J., LINDEIJER, E., ROORDA, A. A. H., VAN DER VEN, B. L. & WEIDEMA, B. P. (2002). *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Centrum voor Milieukunde–Universiteit Leiden (CML). Leiden: Kluwer Academic Publishers.

HAYES, B. J., VAN DER WERF, J. H. J. & PRYCE, J. E. (2011). Economic benefit of genomic selection for residual feed intake (as a measure of feed conversion efficiency) in Australian dairy cattle. *Recent Advances in Animal Nutrition - Australia*, **18**, 31-35.

HEIKKILÄ, A. M., NOUSIAINEN, J. I. & PYÖRÄLÄ, S. (2012). Costs of clinical mastitis with special reference to premature culling. *Journal of Dairy Science* **95**, 139-150.

HUHTANEN, P., RINNE, M. & NOUSIAINEN, J. (2009). A meta-analysis of feed digestion in dairy cows. 2. The effects of feeding level and diet composition on digestibility. *Journal of Dairy Science* **92**, 5031-5042.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Agriculture, Forestry and Other Land Use*, vol. 4 (Eds S. Eggleston, L. Buendia, K. miwa, T. Ngara & K. Tanabe). Hayama, Japan:

Institute for Global Environmental Strategies (IGES).

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) (2007). *Changes in Atmospheric Constituents and in Radiative Forcing*. Chapter 2 in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge: Cambridge University Press.

JONES, H. E., WARKUP, C. C., WILLIAMS, A. & AUDSLEY, E. (2008). The effect of genetic improvement on emission from livestock systems. In: *Proceedings of the European Association of Animal Production*, 24-27 August, Vilnius, Lithuania, p. 28.

KOSSAIBATI, M. A. & ESSLEMONT, R. J. (1997). The cost of production diseases in dairy herds in England. *Veterinary Journal* **154**, 41-51.

MORAN, D., BARNES, A. & MCVITTIE, A. (2007). The rationale for Defra investment in R&D underpinning the genetic improvement of crops and animals (IF0101). *Final report to Defra*. London: Defra.

MINSON, D. J. & MCDONALD, C. K. (1987). Estimating forage intake from the growth of beef cattle. *Tropical Grasslands* **21**, 116-122.

NRC (2001). *Nutrient Requirements of Dairy Cattle*. 7th edition. Washington: National Academies Press.

PRITCHARD, T., COFFEY, M. MRODE, R. & WALL, E. (2012). Genetic parameters for production, health, fertility and longevity traits in dairy cows. *Animal* **7**, 34-46.

PRYCE, J. E., VAN DER WERF, J. H. J., HAILE-MARIAM, M., MALCOLM, B. & GODDARD, M. E. (2009). Updated index weights for the Australian Profit Ranking in dairy. *Proceedings of the Association for the Advancement of Animal Breeding and Genetics*, **18**, 143-146.

REDMAN, G. (2012). *The John Nix Farm Management Pocketbook 2012*. Melton Mowbray:

Agro Business Consultants Ltd.

ROBERTSON, A. & RENDEL, J. M. (1950). The use of progeny testing with artificial insemination with dairy cattle. *Journal of Genetics* **50**, 21-31.

RUTHERFORD, K. M. D., LANGFORD, F. M., JACK, M. C., SHERWOOD, L., LAWRENCE, A. B. & HASKELL, M. J. (2009). Lameness prevalence and risk factors in organic and non-organic dairy herds in the United Kingdom. *Veterinary Journal* **180**, 95-105.

STOTT, A. W., VEERKAMP, R. F. & WASSELL, T. R. (1999). The economics of fertility in the dairy herd. *Animal Science* **68**, 49-57.

STOTT, A. W., COFFEY, M. P. & BROTHERSTONE, S. (2005). Including lameness and mastitis in a profit index for dairy cattle. *Animal Science* **80**, 41-52.

TAKEDA, H. & KIRIYAMA, S. (1978). Correlation between the physical properties of dietary fibers and their protective activity against amaranth toxicity in rats. *Journal of Nutrition* **109**, 388-396.

UK GREENHOUSE GAS INVENTORY (UKGGI) (2010). *1990 To 2010 Annual Report for Submission under the Framework Convention on Climate Change*. London: Defra.

VALLIMONT, J. E., DECHOW, C. D., DAUBERT, J. M., DEKLEVA, M. W., BLUM, J. W., BARLIEB, C. M., LIU, W., VARGA, G. A., HEINRICHS, A. J. & BAUMRUCKER, C. R. (2010). Genetic parameters of feed intake, production, body weight, body condition score, and selected type traits of Holstein cows in commercial tie-stall barns. *Journal of Dairy Science* **93**, 4892-4901.

VALLIMONT, J. E., DECHOW, C. D., DAUBERT, J. M., DEKLEVA, M. W., BLUM, J. W., LIU, W., VARGA, G. A., HEINRICHS, A. J. & BAUMRUCKER, C. R. (2013). Feed utilization and its associations with fertility and productive life in 11 commercial Pennsylvania tie-stall herds. *Journal of Dairy Science* **96**, 1251-1254.

VAN DE HAAR, M. J. & ST PIERRE, N. (2006). Major advances in nutrition: relevance to the sustainability of the dairy industry. *Journal of Dairy Science* **89**, 1280-1291.

VEERKAMP, R. F., EMMANS, G. C., CROMIE, A. R. & SIMM, G. (1995). Variance components for residual feed intake in dairy cows. *Livestock Production Science* **41**, 111-120.

VEERKAMP, R. F. & BROTHERSTONE, S. (1997). Genetic correlations between linear type traits, food intake, live weight and condition score in Holstein Friesian dairy cattle. *Animal Science* **64**, 385-392.

VEERKAMP, R. F. (1998). Selection for Economic Efficiency of dairy cattle using information on live weight and feed intake: A review. *Journal of Dairy Science* **81**, 1109-1119.

VISSCHER, P., GODDARD, M. & BOWMAN, P. (1994). Breeding objectives for pasture based dairy production systems. *Livestock Production Science* **40**, 123-137.

WAINMAN, F. W., DEWY, P. J. S. & BOYNE, A. W. (1981). *Feedingstuffs Evaluation Unit, Third Report 1981*. Aberdeen: Rowett Research Institute.

WALL, E., LUDEMANN, C., JONES, H., AUDSLEY, E., MORAN, D., ROUGHSEDGE, T. & AMER, P. (2010a). The potential for reducing greenhouse gas emissions for sheep and cattle in the UK using genetic selection (FGG0808). *Final report to Defra*. London: Defra.

WALL, E., SIMM, G. & MORAN, D. (2010b). Developing breeding schemes to assist mitigation of greenhouse gas emissions. *Animal* **4**, 366-376.

WILKINSON, J. M. & AUDSLEY, E. (2013) Options from life-cycle analysis for reducing greenhouse gas emissions from crop and livestock production systems. *International Journal of Agricultural Management,* **2**, 70-80.

WILLSHIRE, J. A. & BELL, N. J. (2009). An economic review of cattle lameness. *Cattle Practice* **17**, 136-141.

WILLIAMS, Y.J., PRYCE, J. E., GRAINGER, C., WALES, W. J., LINDEN, N., PORKER, M. & HAYES, B. J. (2011). Variation in residual feed intake in Holstein-Friesian dairy heifers in southern Australia. *Journal of Dairy Science* **94**, 4715-4725.

WRIGHT, I. A. (1982). *Studies on the Body Composition of Beef Cows*. Ph.D. thesis, University of Edinburgh.

Table 1. *Production values included in the model for an average cow in the UK*

	Units	Average
Age at first calving	days	730
Lactations	No.	2.91
Growth rate	kg protein/d	0.0033
Empty body weight	kg	550
Mature milk volume*	litres/lactation	10,080
Milk protein*	%	3.22
Milk fat*	%	3.98
Gestation	days	283
Lactation length*	days	344

* From CDI (2013)

Table 2. *Modeled average milk fat yield, milk protein yield, dry matter (DM) intake, somatic cell count (SCC), calving interval, mastitis incidence, lameness incidence, survival and long-run steady state for a 100 cow herd from the Markov chain for an average herd in the baseline situation for a heifer replacement and lactations 1 to 12*

	Milk fat	Milk protein	DM intake	SCC*	Interval†	Mastitis	Lameness	Chance of being culled*	Steady-state herd
Age group	kg/lactation	kg/lactation	kg/d	'000 cells/ml	days	%	%		hd/100 cows
Heifer	-	-	4.5	-	730	-	-	0	34.4
1	288	233	16.1	133	415	13.6	12.9	0.20	28.5
2	365	295	18.8	161	416	18.1	15.9	0.23	22.7
3	390	316	19.6	204	419	25.0	18.9	0.28	17.6
4	398	322	19.8	259	420	33.1	21.9	0.34	12.6
5	399	323	19.9	313	420	40.4	24.9	0.42	8.3
6	402	325	19.8	356	424	45.3	27.9	0.45	4.8
7	403	326	19.8	383	427	48.2	30.9	0.44	2.6
8	397	322	19.7	398	424	49.8	33.8	0.48	1.5
9	395	320	19.5	405	426	50.5	36.8	0.49	0.8
10	381	308	19.3	409	418	50.9	39.8	0.61	0.4
11	386	313	18.9	411	434	51.1	42.8	0.64	0.2
12	374	302	18.4	412	434	51.2	45.8	1	0.1

[*] From CDI (2013).

[†] Heifers assumed to enter the milking herd at 730 days of age, with calving intervals obtained from CDI (2013).

Table 3. *Assumed nutrient composition of pasture, grass silage and dairy concentrate*

	Units	Pasture	Grass silage	Concentrate
Dry matter digestibility at maintenance (DMD_m)[*]	% of DM	71.8	75.5	78.1
Organic matter digestibility at maintenance (OMD_m)[†]	% of OM	72.3	75.4	77.4
CP[‡]	g/kg DM	225	158	296
Digestible CP[§]	g/kg DM	189	126	260
NDF[‡]	g/kg DM	627	498	222
Ether extract[‡]	g/kg DM	22	44	50
Ash[‡]	g/kg DM	31	78	96
Non-fiber carbohydrate[§]	g/kg DM	95	222	336
Undigested organic matter[§]		3.34	3.28	3.33
Gross energy (GE)[‡]	MJ/kg DM	18.5	19.2	20.5
Metabolisable energy (ME)[‡]	MJ/kg DM	10.5	11.5	12.7

[*] Using equation of Minson & McDonald (1987).

[†] Estimated from Rowett Feedingstuffs Evaluation Unit Third Report data (Wainman *et al.*, 1981) as: $\% \ OMD_m = 14.36 + 1.0183 \times (ME / GE) \times 100$.

[‡] From Bell *et al.* (2011), except for ether extract from FeedByte® model.

[§] Digestible CP (kg/kg DM) = CP – (((0.3 × (1 - (DMDm + 0.1))) × CP) + (0.105 × ME × 0.008) + 0.0152); Non-fiber carbohydrate = 1000 - (NDF + ash + crude protein + ether extract); Undigested organic matter = reciprocal of undigested organic matter plus ash content (g/kg DM) of feed at maintenance intake level.

Table 4. *Assumed income and costs associated with production for an average herd obtained from Redman (2012)*

		Average
Income	Units	£/unit
Milk fat[*]	kg	2.42
Milk protein[*]	kg	4.40
Bull calf	kg dead weight	1.05
Heifer calf	Head	200
Culled cow	kg dead weight	0.73
Costs		
Milking herd replacement[†]	Head	1400
Charge on volume	Litres	0.027
Enterprise[‡]	kg milk solids	0.45
Labor[§]	Hour	10
Semen	per straw	30
Pasture	MJ metabolisable energy	0.005
Grass silage	MJ metabolisable energy	0.007
Concentrate	MJ metabolisable energy	0.020

[*] Based on milk compositions for milk fat and protein in table 1 and an average price of 24 pence per litre of milk.

[†] Feed costs were deducted to give a non-feed cost associated with a milking herd replacement in the model

[‡] Herd test, animal health, housing and dairy supplies.

[§] Assumed cost of 30 minutes per artificial insemination, 50 minutes per case of severe and fatal clinical mastitis (P. Down, The University of Nottingham, Sutton Bonington, UK, personal communication) and 15 minutes for digital lameness, 12 minutes for interdigital lameness and 20 minutes per case of sole ulcer lameness (Kossaibati & Esslemont, 1997).

Table 5. *Percentage of total energy (% of ME) for a heifer replacement and the average lactating dairy cow for maintenance (E_{maint}), protein growth (E_p), lipid growth (E_l), pregnancy (E_{preg}), activity (E_{act}) and milk production (E_{lact}) over a lifetime*

Energy requirement	Heifer	Lactating
E_{maint}	48.3	23.3
E_p	12.3	0.1
E_l	26.9	0.6
E_{preg}	7.7	3.8
E_{act}	4.8	2.3
E_{lact}	0.0	69.9
Total per age group (MJ)	28249	72414

Table 6. *Average values per cow for production and fitness traits, and nitrogen (N) excretion, enteric and manure methane (CH_4) and nitrous oxide (N_2O) emissions for a long-run steady state herd*

Trait	Units	per cow
Milk volume	litres/lactation	8965
Milk fat yield	kg/lactation	358
Milk protein yield	kg/lactation	290
Live weight	Kg	632
Body condition score	1 to 9 scale	4.5
Survival	%/lactation	71.5
DM intake *	kg/d	20.1
Somatic cell count	‘000 cells/ml	208
Mastitis	%/lactation	24.8
Lameness	%/lactation	18.6
Calving interval	days/lactation	418
N excretion *	kg/d	0.59
Enteric CH_4 *	g/d	395
Manure CH_4 *	g/d	114
Manure N_2O *	g/d	22

* Includes contribution from herd replacements.

Table 7. *Assumed percentage of manure produced by management system for a herd replacement and lactating cow for an average system, and emission factors used to calculate the greenhouse gas emissions (UKGGI, 2010)*

	Manure produced (%)		Fraction of nitrogen lost	Nitrous oxide	Methane conversion factor
	Heifer	Lactating	N/N present	kg of N_2O/kg of N	%
Solid storage	3.6	12.9	0.35	0.02	1
Liquid system	38.3	9.1	0.4	0.001	39
Daily spread	13	9	0.07	0.0125	0.1
Grazing animal	45.1	69	0.2		1
Urine				0.02	
Dung				0.02	
Leaching			0.3	0.025	
Atmospheric deposition				0.01	

Table 8. *Change in profit and carbon dioxide (CO_2-eq.) emissions per cow and per kilogram milk solids (MS) associated with a 1 unit increase in milk volume, fat yield, protein yield, live weight, body condition score, survival, residual feed intake, somatic cell count (SCC), mastitis incidence, lameness incidence and calving interval for an average herd over the lifetime of a cow*

		Change in profit	Carbon dioxide emissions	
Trait	Units	£	kg CO_2-eq./cow	g CO_2-eq./MS
Milk volume	litres/lactation	-0.08	0.2	0.2
Milk fat	kg/lactation	1.44	7.8	-8.5
Milk protein	kg/lactation	3.90	2.2	-17.0
Live weight	kg	-0.36	4.1	8.6
Condition score	1 to 9 scale	-13.56	23.1	191.8
Survival	%/lactation	9.59	-6.9	-44.4
Residual feed intake	kg/d	-52.23	662	1026
SCC	‘000 cells/ ml / lactation	-0.31	0.1	0.2
Mastitis	%	-1.06	0.4	0.7
Lameness	%	-1.11	0.3	0.5
Calving interval	days/lactation	-2.19	11.3	8.6

Table 9. *Expected annual response per cow based on the biological variation in breeding objective traits and their economic values in table 8 using a multi-trait selection index*[*]

Trait	Units	Phenotypic standard deviation[*]	Genetic standard deviation[*]	Annual response[†] per unit	Annual response[†] £
Milk volume	litres	1875	1027	121.74	-9.90
Milk fat yield	kg	72	37	6.31	9.10
Milk protein yield	kg	57	30	5.21	20.34
Live weight	kg	75	50	3.30	
Body condition score	1 to 9 scale			-0.01	
Survival	%	29	6	0.79	7.61
Dry matter intake	kg			0.10	
Residual feed intake	kg	1.45	0.79	-0.01	0.58
Somatic cell count	‘000 cells/ml	78	29	-1.17	0.37
Mastitis	%	38	8	-0.57	0.61
Lameness	%	37	5	-0.12	0.13
Calving interval (fertility)	days	61	12.2	-0.08	0.18
Total					29.02

[*] The phenotypic standard deviation (σp) and heritability (h^2) were used to calculate the genetic standard deviation (σa) using the formula σa = σp × h, where h is the square root of the heritability. For most traits the phenotypic standard deviation (σp) and heritability (h^2) was obtained from Pritchard *et al.* (2012), except for live weight (σp from Bell *et al.* (2011) and h^2 from Veerkamp and Brotherstone (1997)), condition score (σp from Banos *et al.* (2006) and h^2 from Veerkamp and Brotherstone (1997)), and DM intake and residual feed intake (σp and h^2 for DM intake from de Haas *et al.* (2012) and residual feed intake from Veerkamp *et al.* (1995)).

[†] It was assumed that residual feed intake was only available as a genomic breeding value, whereas breeding values for the other traits were available from progeny-testing, with bulls having 80 daughters for production trait estimates and 40 daughters for health and fertility traits estimates. Annual response calculated based on a 0.22 standard deviation change in the aggregate index value (Robertson & Rendel, 1950).

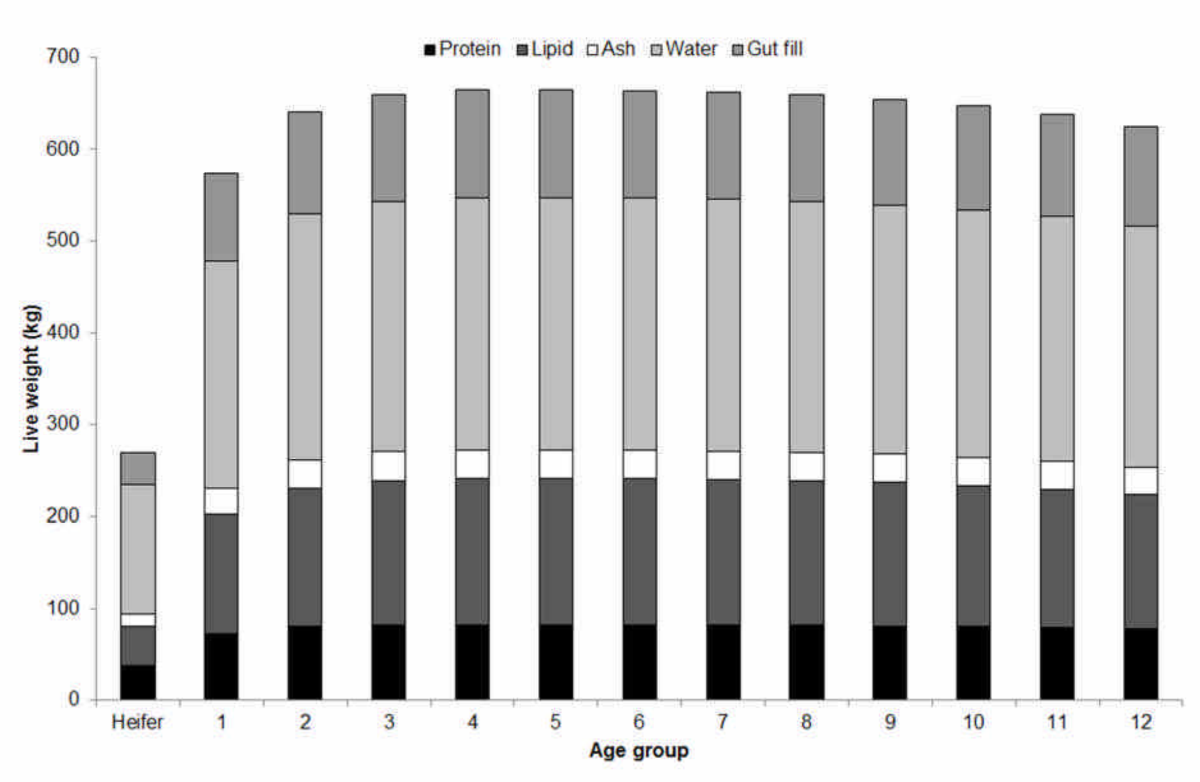

Figure 1. *Average mass of protein, lipid, ash, water and gut fill in the live weight of an average heifer replacement and a dairy cow from lactations 1 to 12 with a mature empty body weight of 550 kg.*

APPENDIX

The methodology for costs associated with an incidence of mastitis and lameness (Table A) were based on Kossaibati & Esslemont (1997). The costs of treatment for mastitis (P. Down, The University of Nottingham, Sutton Bonington, UK, personal communication) and lameness (Willshire & Bell, 2009) were revised, as well as the costs of production (Table 4). The average amount of milk lost (discarded and reduced) over a cow's lifetime were about 5 and 2.3% for clinical and subclinical mastitis and 5.6 and 2% for clinical and subclinical lameness respectively.

Table A. *Costs (£ unless otherwise shown) of a mastitis and lameness case*

	Mastitis				Lameness			
	Clinical			Subclinical	Clinical			Subclinical
	Severe	Mild	Fatal		Digital	Interdigital	Sole ulcer	
Prevalence[*]	*0.15*	*0.84*	*0.01*		*0.47*	*0.22*	*0.31*	
Treatment[a]	40.00	5.58	40.00		12.90	11.28	12.01	
Vet visit[b†]	62.50		62.50		18.75	15.00	25.00	
Herdsman's time[c†]	5.00	2.50			30.00	10.00	50.00	
Discarded milk[d†]	52.48	40.82			40.82	29.16	34.99	
Reduced yield[†]	83.20	46.29		46.29	70.45	40.26	110.70	40.26
Fatality[†]			1684.22					
Risk of culling[†]	80.30	40.15		8.03	44.17		72.27	
Extended calving interval[†]					19.80	37.40	88.00	
Per case	323.48	135.34	1786.72	54.32	236.88	143.09	392.97	40.26
Per repeat case (a+b+c+d)	159.98	48.90			102.47	65.44	122.00	
Total per cow[‡]	387.47	154.90	1786.72	54.32	277.87	169.27	441.77	40.26
Cost per incidence based on prevalence	206.11			54.32	304.79			40.26
Discarded milk per case (litres)	348.23	270.85			270.85	193.46	232.15	
Discarded	279.75				232.15			

milk per incidence (litres)

[*] Prevalence of cases reported by Kossaibati & Esslemont (1997) were used for lameness since they were consistent with a more recent study (Barker, 2007), whereas the prevalence of mild and severe clinical mastitis were changed to represent current levels (P. Down, The University of Nottingham, Sutton Bonington, UK, personal communication).

[†] Veterinarian's time at £75 per hour; Labour at £10 per hour; Milk discarded for 9 and 7 days for a severe and mild clinical case of mastitis and 7, 5 and 6 days for a digital, interdigital and sole ulcer clinical case of lameness respectively; Milk reduced by 4.1 and 2.3% for a severe and mild clinical case of mastitis and 3.5, 2 and 5.5% for a digital, interdigital and sole ulcer clinical case of lameness respectively; Cost of a fatality was the cost of a heifer replacement minus the value of a cull cow, the difference in the value of milk yielded by a mature cow and a heifer and the difference in the value of a mature cow's calf and a calf from a heifer; Cost of culling was the value of a cull cow multiplied by the increased chance of being culled of 20, 10 and 2 % for a severe, mild and subclinical case of mastitis and 11 and 18% for a digital and sole ulcer case of lameness respectively; Calving interval increased by 9, 17 and 40 days for a digital, interdigital and sole ulcer cases of lameness respectively, multiplied by the cost per day for an increased calving interval.

[‡] Assuming cows average 1.4 cases per incidence of severe and mild mastitis and clinical lameness (Pritchard *et al.* 2012).