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ORIGINAL RESEARCH

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Estimated differences in economic and environmental performance of forage-based dairy herds across the UK

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Abstract

Differences in performance among the areas of England, Scotland, Wales, and Northern Ireland can provide some insight into the resilience of UK milk supplies from forage-based dairy herds. This study used a Markov Chain approach to model the average herd in each region between the years 2010 and 2015. The effect of a single unit change in milk production (milk volume, fat yield, and protein yield), fitness (survival, somatic cell count, mastitis, and calving interval) and efficiency (methane) traits on the economic value and GHG emissions intensity (expressed as carbon dioxide equivalents per cow and per kg milk solids) were assessed. Production data were obtained from a total of about half a million milk recorded dairy cows in the UK and the Farm Business Surveys for each region. Across the UK improving the health somatic cell counts (SCC and mastitis), fertility (calving intervals) and survival of cows will increase profitability and reduce emissions intensity of milk production. In Scotland, herds had higher milk yields but poorer survival, which potentially could be due to poor fertility indicated by a longer calving interval compared to other regions. Herds in Northern Ireland had the shortest average calving interval but the highest SCC, and thus greater estimated mastitis incidence and wasted milk. Notably, England had considerably higher economic values (between 10% and 30%) and emission intensity values (between 11% and 37%) for SCC and mastitis incidence than other regions, due to lost milk production and the higher gross margin. This study provides a framework that can be customized for individual herds to allow assessment of resilience and resource efficiency of milk production not only in the UK but for comparison with international dairy systems.

KEYWORDS

biological traits, dairy systems, greenhouse gas emissions, profit

1 | INTRODUCTION

The UK is a significant global producer of milk, with about 1.8 million cows producing 14 ml of milk each year (valued at £4bn), making the UK the tenth largest global milk producing country (FAO, 2017). Traditionally, dairy cows in the UK are housed throughout the winter months and fed conserved forages (e.g., grass, maize and/or wholecrop silage) and graze pasture when possible during the remaining months of the year. The use and availability of pasture and/or conserved forage as food is a necessity for ruminant livestock such as a dairy cow, as well as providing an affordable source of nutrients in the diet. About 66% of UK agricultural land is grassland (Defra, 2015), which dominates the western part of the country where the majority of dairy cows are found. Overall, approximately 42 million tons of forage dry matter is consumed by ruminant livestock each year, with 70% being pasture and 30% conserved forage (Wilkinson, 2011).

Over the last thirty years the average milk yield of dairy cows in developed countries has been steadily increasing, even with more emphasis being put on health and fertility traits (approximately equal weighting with milk production traits) in genetic selection programs (Eggar-Danner et al., 2015). The higher milk yielding dairy herds rely more on high energy dense diets, and include more cereal-based concentrate feed in the diet (Eastridge, 2006). Cereal-based concentrate feed can be more consistent in nutrient content than forage, but is costly and also more vulnerable to changes in market price (depending on ingredients used). Furthermore, use of bought-in concentrates to the farm contribute to a higher carbon footprint for milk than home-grown forage (Thomassen, van Calker, Smits, Iepema, & de Boer, 2008). Ramsbottom, Horan, Berry, and Roche (2015) studied regional differences for Irish dairy herds using farm-level physical and financial data and found that pasture-based systems with limited supplementary feed inputs delivered the greatest profits and, by virtue of their lower production costs, protected the farm business from milk and feed price volatility. Given that feed costs associated with a production system can be as much as 70% of variable costs (Redman, 2015), particularly if reliant on high inputs of concentrates, effective utilization of home-grown and bought-in feeds is important to the profitability and environmental footprint of the business. In dairy cows, although the carbon dioxide equivalent (CO_2-eq.) emissions per liter of milk appears to have reduced due to a dilution in animal maintenance requirements with increased average milk yields per cow (Capper, Cady, & Bauman, 2009), there is little evidence to suggest that improvements in fitness traits has been made with regard to health (e.g., mastitis, lameness) and fertility during this time (FAWC, 2009). High milk yielding cows mobilize body fat reserves for milk production which can be detrimental to the health and fertility of the cow (Pryce, Nielson, Veerkamp, & Simm, 1999) and its subsequent lifespan (Bell, Wall, Russell, Roberts, & Simm, 2010). Inefficiencies in the total output of milk produced can be caused by factors such as poor animal health and wellbeing, and animal nutritional requirements not being met, which may also be linked to the genetic background of the individual animal (i.e., genotype × environment interaction) (Dillon, Berry, Evans, Buckley, & Horan, 2006).

Improvements in production efficiencies and profitability of milk produced from dairy cows is of great interest to farmers and the sustainable intensification of milk supplies, with the added benefit of efficiency savings also helping to reduce nutrient losses and GHG emissions (i.e., methane [CH_4] and nitrous oxide [N_2O]) associated with milk products, which is socially important (Bell, Wall, Russell, Simm, & Stott, 2011). Given that the UK is the 10th largest milk producer globally, achieving reductions in CH_4 and N_2O losses to the environment are key environmental benefits; this paper explores the potential for environmental improvements across the regions of the UK, drawing upon a combination of detailed biophysical trait, and farm business economic data.

This study used the model by Bell (2015) and Bell, Garnsworthy, Stott, and Pryce (2015) to assess the impact on economic value (£/cow) and GHG emissions intensity (CO_2-eq. emissions per cow and per unit milk solids) of a unit increase in selected biological traits associated with dairy cows. Data for the average herd in England, Scotland, Wales, and Northern Ireland were used to assess differences among regions of the UK.

2 | MATERIALS AND METHODS

2.1 | Data

Average production records between the years 2010 and 2015 were obtained for dairy cows in England ($n = 346{,}538$), Scotland ($n = 51{,}904$), Wales ($n = 65{,}725$), and Northern Ireland ($n = 46{,}713$) from the Centre for Dairy Information (CDI, 2016) for milk recorded herds (Table 1). The data provide a representation of herds across the UK to assess regional differences. The use of average values allowed data from the Farm Business Surveys for each region and representative diet composition information (Bell, 2015) to be combined for the analysis.

2.2 | Herd structure

This study used an existing economic model (for more detail see Bell, 2015; Bell, Eckard, Haile-Mariam, & Pryce, 2013; Bell, Garnsworthy et al., 2015) to dynamically describe the nutrient partitioning of a cow using a Gompertz growth curve (growth rate of 0.0033 kg protein per day) over its lifetime. The model allows herd level data to be combined and cow biological traits to be adjusted, in order to test the impact of trait adjustments on the key production, environmental and economic metrics flowing from dairy production that cannot be explored through the static analysis of individual datasets alone. Responses to changes are quantified by calculating differences between the current state (baseline situation) and an increase in a biological trait (altered situation). A total of 11 age groups including heifer replacements and 10 lactations for milking cows were modeled. A Markov chain was used to obtain a steady-state herd structure for each age group to allow the effect of survival within a population to be investigated. 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,

TABLE 1 Average production values per lactation for herds in England, Scotland, Wales, and Northern Ireland

Trait	Units	England	Scotland	Wales	NI
Milk volume[a]	Liters	9,025	9,189	8,664	8,744
Milk fat yield[a]	kg	359	363	344	349
Milk protein yield[a]	kg	287	290	275	278
Survival[a]	%	71	69	71	70
Somatic cell count[a]	'000 cells/ml	183	198	199	237
Calving interval[a]	days	413	418	416	411
Dry matter intake[b,c]	kg	10,678	10,970	10,506	10,602
Enteric CH_4[c,d]	kg	249	257	249	250
Manure CH_4[c]	kg	48	49	47	47
Total N_2O[c,e]	kg	11	11	11	11
$C0_2$ equivalent emissions	tons	8.3	8.4	8.2	8.2
Stocking rate	Cows per forage hectare	2.1	2.1	2.2	2.2

[a]Data from CDI (2016).
[b]Feed intake was calculated from total metabolizable energy (ME) requirement as: Feed intake (kg DM/day) = $E_{total} \times 1/(\text{ME} - 0.616 \times E_{CH_4} - 3.8/\text{FE} - 29.2 \times \text{DCP}/6.25)$, where ME, E_{CH_4}, GE_f and FE are the metabolizable, enteric CH_4 (both MJ/kg DM), gross fecal and fecal energy (both MJ/kg OM) and DCP is the digestible crude protein (kg/kg DM).
[c]Includes contribution from herd replacements.
[d]Enteric CH_4 emissions were estimated by: CH_4 (g/kg DM intake) = 0.046 × DOMD − 0.113 × ether extract (both g/kg DM) − 2.47 × (feeding level − 1), where DOMD is digestible organic matter in the dry matter and feeding level is metabolizable energy intake as multiples of maintenance energy requirements.
[e]Includes direct (from stored manure and application of feces, urine, and manure) and indirect N_2O from storage and application of manure to land (from leaching and atmospheric deposition of nitrogen from NO_x and NH_3) as attributed in the UK National GHG Inventory for agricultural production (UKGGI, 2010).

Veerkamp, & Wassell, 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. 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. Cow values were multiplied up to a 100 cow herd, to allow investigation of changes in profit and CO_2-eq. emissions per unit product in response to changes in biological traits. Replacement animals were assumed to calve at 2 years of age. 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 male calves sold were assumed to leave the system immediately after birth.

2.3 | Energy requirements and feed intake

It is assumed in the model that energy requirements (of herd replacements and lactating cows) for maintenance, growth, pregnancy, activity, and lactation are achieved and that feed intake is always sufficient to achieve energy requirements in the baseline situation. Metabolizable energy (ME, MJ/day) 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 based on average production data for each region (Table 1) are presented in Table 2.

The associated feed intake required is then formulated based on the average herd replacement and lactating cow consuming a ration containing pasture, grass silage, and dairy concentrate (Table 3), as found appropriate to represent UK systems by Bell (2015). The diet was constrained to a maximum of 50% pasture per kilogram of fresh feed.

A unit reduction in DM intake assumed that ME requirement of the animal remained constant in the baseline and altered situations, but ME intake and associated cost of consumed feed were lower to represent an improvement in feed intake. The cost of feed consumed by each age group was estimated by multiplying total DM intake by ME

TABLE 2 Percentage of total metabolizable energy (% of ME) for a herd replacement and the average lactating dairy cow in England, Scotland, Wales, and Northern Ireland (NI) 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 based on the modeled baseline production data

Energy requirement	Replacement[a]	England	Scotland	Wales	NI
		Lactating cow			
E_{maint}	53.9	27.7	27.6	28.5	28.0
E_p	11.2	0.3	0.3	0.3	0.3
E_l	19.2	1.1	1.1	1.1	1.1
E_{preg}	10.3	6.0	6.0	6.2	6.2
E_{act}	5.4	2.8	2.8	2.8	2.8
E_{lact}	0.0	62.1	62.2	61.0	61.6
Total per age group (MJ)	41,067	76,831	77,255	74,847	74,972

[a]Assumed to be similar across regions.

TABLE 3 Assumed content and composition of a herd replacement and lactating cow diet[a]

Nutrient content	Units	Replacement	England	Scotland	Wales	NI
Crude protein (CP)	g/kg DM	192	196	196	196	196
Neutral detergent fiber (NDF)	g/kg DM	423	392	392	392	392
Ether extract	g/kg DM	37	35	35	35	35
Ash	g/kg DM	70	80	80	80	80
Metabolizable energy (ME)[b]	MJ/kg DM	11.5	11.2	11.2	11.4	11.4
Digestible energy (DE)[b]	MJ/kg DM	13.9	13.4	13.4	13.6	13.5
Gross energy (GE)	MJ/kg DM	19.2	19.4	19.4	19.4	19.4
Feeding level[b]		1.4	3.4	3.5	3.3	3.3
Digestible organic matter in dry matter (DOMD)[c]	g/kg DM	716	705	705	712	711
Organic matter digestibility (OMD)[b]	% of OM	77.7	76.6	76.6	77.3	77.3
Digestible CP[b]	g/kg DM	133	137	137	137	137
Methane[c]	g/kg DM	27.6	22.5	22.4	23.1	23.0
Composition						
Pasture	%	40	33	33	33	33
Conserved forage	%	40	33	33	33	33
Concentrate	%	20	34	34	34	34

[a]Nutrient compositions for UK systems from Bell (2015).
[b]The ME and DE were adjusted for feeding level, with feeding level calculated as ME intake as multiples of animal maintenance energy requirements (AFRC, 1993). The DE content was estimated from GE content and energy lost in feces.
[c]The DOMD was estimated from Wainman, Dewy, and Boyne (1981) as: DOMD (g/kg DM) = 472.49 × ln(ME) − 437.69; % OMD = [DOMD/(1,000 − ash)] × 100; Digestible CP (g/kg DM) was estimated by the rearranged equation of Wang et al. (2009) as = CP − [((ln((OMD/100 − 0.899)/−0.644) × 100)/−0.5774)/1,000] × ((1,000 − ash) − DOMD); Enteric CH_4 emissions were estimated as: CH_4 (g/kg DM intake) = 0.046 × DOMD − 0.113 × ether extract − 2.47 × (feeding level − 1).

content (Table 3) and cost per unit ME of the diet (assumed cost for pasture was £0.003 per MJ ME, grass silage was £0.009 per MJ ME and concentrates £0.02 per MJ ME from Redman (2015)). Feed intake of an animal was calculated by Equation (1) from total ME requirement as:

$$\text{Feed intake (kg DM)} = E_{total} \times 1/(\text{ME} - 0.616 \times E_{CH_4} - 3.8/\text{FE} - 29.2 \times \text{DCP}/6.25) \quad (1)$$

where ME, FE, UE and E_{CH_4} is the metabolizable, fecal, urine, and enteric CH_4 energy (all MJ/kg DM). The values of 0.616, 3.8, and 29.2 are the heat increments associated with fermentation, feces and urine. The loss of nutrients in feces and urine was calculated from the undigested organic matter and crude protein (Table 3).

2.4 | Greenhouse gas emissions

Sources of GHG emissions were from enteric and manure CH_4 and direct (from stored manure and application of feces, urine and manure) and indirect N_2O from storage and application of manure to land (from leaching and atmospheric deposition of nitrogen from NO_x and NH_3) as attributed in the UK National GHG Inventory for agricultural production (UKGGI, 2010). The IPCC (2007) 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 feces (N intake − digested N intake) and urine (N intake − (N retained + N in feces)). Emission factors for manure CH_4 and N_2O are shown in the Appendix (Table A1). Based on UK GHG inventory values the following were fixed in the calculations: CH_4 conversion factor of 0.662 m^3/kg CH_4 and CH_4 producing capacity of manure of 0.24 m^3/kg volatile solids (UKGGI, 2010). Volatile solids in manure were calculated from the undigested organic matter (1—digestible organic matter kg/kg). Emissions were expressed as CO_2-eq. emissions per cow and per kilogram of milk solids. Kilograms of CO_2-eq. emissions for a 100-year time horizon were calculated using conversion factors from CH_4 to CO_2 of 25 and from N_2O to CO_2 of 298 (IPCC, 2007). The loss of dietary energy as enteric CH_4 was calculated using Equation (2) by Bell, Eckard, Moate, and Yan (2016):

$$\begin{aligned}CH_4(\text{g/kg DM intake}) = {} & 0.046 \times \text{DOMD} - 0.113 \\ & \times \text{ether extract (both g/kg DM)} - 2.47 \\ & \times (\text{feeding level} - 1)\end{aligned} \quad (2)$$

where DOMD is digestible organic matter in the dry matter and feeding level is metabolizable energy intake as multiples of maintenance energy requirements. The CH_4 emissions for lactating cows (22.4–23.1 g/kg DM intake, Table 3) and herd replacements (27.6 g/kg DM intake) is consistent with chamber measurements for cattle (22.3 g/kg DM intake for lactating cows and 26.5 g/kg DM intake for beef cattle) fed a similar high-forage diet (Bell, Eckard et al., 2016). Losses of CH_4 and N_2O emissions were assumed to be linearly related to all biological traits except survival (a curvilinear relationship with survival is generated by the Markov chain).

2.5 | Calculation of per cow lactation yields

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. Amounts of milk protein, fat, and lactose produced were calculated based on the average milk fat of 4.0% and protein 3.2% contents, which was found to be the same for each region, and an assumed milk content of 5% lactose (Reece, Erickson, Goff, & Uemura, 2015).

2.6 | Fertility and health

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 estrus (days))/21), where the start of an estrous cycle was assumed to be 426 days after birth of a herd replacement and 82 days after calving for a lactating cow. Gestation length was assumed to be constant at 283 days. 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. The cost of poor fertility was calculated from the cost of each insemination (labor cost at £10 per hour/2 + semen straw cost of £15 each), the additional feed consumed by a milking cow, and the cost of a milking herd replacement per extra day required. The percentage of cows in each lactation that had mastitis was calculated using a cumulative normal distribution with a mean log transformed SCC of 400,000 somatic cells/ml (de Haas, Veerkamp, Barkema, Gröhn, & Schukken, 2004). A cow with mastitis had an associated cost for treatment and loss of milk (Appendix, Table A2). For mastitis, on average 0.25 incidences were assumed to be clinical cases, with the remainder assumed to be subclinical cases. In addition to the costs of fertility and

TABLE 4 Modeled incidence (%) and cost (£ per cow) for main health problems for steady state herds in England, Scotland, Wales, and Northern Ireland

	Incidence				Cost			
	England	Scotland	Wales	NI	England	Scotland	Wales	NI
Mastitis	21.1	23.4	23.6	29.0	32.49	33.41	31.80	35.12
Hoof dermatitis	25.9	25.9	25.9	25.9	57.99	58.03	55.11	55.51
Hoof lesion	28.5	28.0	28.5	28.4	96.18	94.31	91.50	91.60
Uterine discharge	16.2	16.2	16.2	16.2	15.72	15.82	14.78	14.90
Retained placenta	5.7	5.6	5.8	5.7	6.54	6.39	6.10	6.11
Milk fever	5.3	4.9	5.3	5.2	4.34	4.02	4.10	4.05
Estrus not observed	40.9	41.2	40.8	40.9	6.61	6.67	6.59	6.61
Assisted birth	16.3	16.7	16.4	16.5	4.65	4.79	4.61	4.66

TABLE 5 Income and output costs (£) calculated for the baseline steady state herd per cow (including herd replacements and milking herd)

	England	Scotland	Wales	NI
	£	£	£	£
Income				
Milk sales[a]	2,617.33	2,637.47	2,426.02	2,448.38
Calves[b]	218.40	218.01	216.85	217.40
Culls[c]	196.74	214.82	199.68	205.77
Less				
Replacements[d]	−517.37	−563.41	−525.93	−541.19
Total output	2,515.10	2,506.89	2,316.63	2,330.36
Variable costs				
Feed	1,277.00	1,309.52	1,254.96	1,265.67
Dairy supplies[e]	183.86	187.11	176.48	178.11
Health problems	224.52	223.45	214.59	218.55
Fertility	84.45	90.88	87.70	83.29
Total variable costs	1,769.83	1,810.95	1,733.73	1,745.62
Gross Margin	745.27	695.94	582.89	584.74

[a]The average milk price was 28.5 p/L for England, 28.7 p/L for Scotland, 28.0 p/L for Wales, and 28.0 p/L for Northern Ireland.
[b]Average calf value of £2.50 per kilogram body weight across regions.
[c]Average cull cow value of £0.70 per kilogram body weight across regions.
[d]Average heifer cost of £2.00 per kilogram body weight across regions.
[e]Average cost of £0.02 per liter milk for recording, parlour consumables, sundries across regions.

mastitis, the associated cost for other notable health problems were included in the farm gross margin, which were hoof dermatitis, hoof lesions, uterine discharge, retained placenta, milk fever, estrus-not-observed and assisted births (Table 4). The incidence of common health problems in each lactation and representative of UK dairy systems were obtained from Bell et al. (2010) and modeled for the steady-state herd in each region. The same approach as Kossaibati and Esslemont (1997) was used to cost health problems, but treatment costs were revised to represent current values. Furthermore details regarding prevalence, incidence, treatments, and input costs associated with health problems for UK dairy systems are described by Bell, Pryce et al. (2016) and shown in the Appendix (Table A2).

2.7 | Change in profit and efficiencies of production

The economic value and emissions intensities as CO_2-eq. emissions per cow and per kg milk solids (environmental impact) were calculated by a single unit increase in each biological trait, and used as a measure of production efficiency. The model included a partial budget calculation to determine the change in gross profit or economic value (e.g., income − variable costs = gross profit or loss) per cow for each age group in the herd for a change in each trait. The average variable costs and income during the study period were obtained from the Farm Business/Accounts Surveys for England (http://www.farmbusinesssurvey.co.uk/), Scotland (http://www.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/Publications/FASdata), Wales (https://www.aber.ac.uk/en/ibers/research/fbs/stats/) and Northern Ireland (https://www.daera-ni.gov.uk/publications/farm-incomes-northern-ireland-2004-2014) to derive gross margins for herds in each region and specific economic values for biological traits (Table 5). The gross margin includes the cost of common health and fertility problems. A single phenotypic change was assessed for the following traits: milk volume, fat yield, protein yield, survival, SCC, mastitis, calving interval, and enteric CH_4 emissions. The traits represented a range of production, health, fertility, and efficiency traits.

3 | RESULTS AND DISCUSSION

Modern dairy cows are associated with increased milk production per cow, greater response of milk production to concentrate supplementation and reduced health and fertility (Dillon et al., 2006). The average milk yields per lactation were 9,025 L in England, 9,189 L in Scotland, 8,664 L in Wales, and 8,744 L in Northern Ireland, with similar contents of milk fat of 4.0 g/kg and milk protein of 3.2 g/kg in each region (Table 1). To achieve these average milk yields the estimated total DM intakes per lactation were 10.7 tons in England, 11.0 tons in Scotland, 10.5 tons

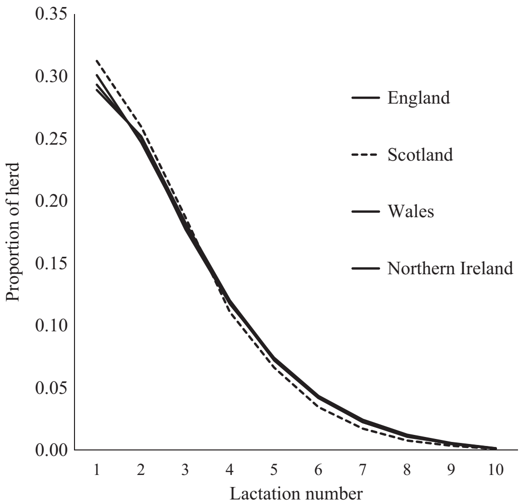

FIGURE 1 Steady-state herd showing proportion of cows in each lactation for UK regions studied

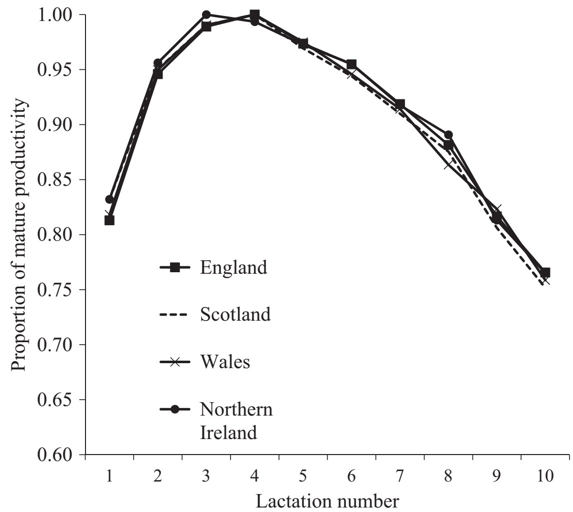

FIGURE 2 Steady-state herd showing proportion of cows in each lactation for UK regions studied

in Wales, and 10.6 tons in Northern Ireland, which included a contribution for feed consumed by the required number of milking herd replacements (Table 1). Based on the estimated feed intake and diet composition of forage and concentrate, the feed costs were 72% of total variable costs (Table 5) across regions. While the modeled herds in Scotland produced more milk, the average number of lactations of 2.6 was lower than in other regions, and herds contained a higher proportion of first to third lactation cows; as well as noticeably fewer cows achieving greater than three lactations than in other regions (Figure 1). The average herd in Northern Ireland also contained a high proportion of cows in their first lactation. The proportion of cows in their second lactation or more for the average herd in England, Wales, and Northern Ireland were similar and hence the average number of lactations was similar at 2.75, 2.76, and 2.73, respectively. The lower survival rate of milking cows in Scottish herds means fewer cows reach their mature productivity of between three and four lactations for milk production (Figure 2) and more milking herd replacements are needed (i.e., impacts on the productivity and profitability of the herd), as at a low rate of survival the cost of milking herd replacements is high but at too high a rate the genetic progress of the herd may be impaired (Hadley, Wolf, & Harsh, 2006). The optimum culling rate within a herd is between 25% and 30% (Bascom & Young, 1998), which is not the case for the average Scottish herd (31%) compared to England (29%), Wales (29%), and Northern Ireland (30%). Bascom and Young (1998) put the main reasons for culling as reproduction, milk production, and mastitis. In Scotland, the poorer survival could be the result of poor fertility, which is indicated by the longer average calving interval of 418 days observed for Scottish herds compared to other regions studied (ranging from 411 to 416 days). As discussed previously, high milk yielding cows, such as in Scotland, mobilize body energy reserves for milk production, with a potential deleterious effect on cow fertility (Pryce et al., 1999). While the average herd in Northern Ireland had a lower average milk yield (8,744 L per lactation) and calving interval (411 days), the average SCC (237,000 cells/ml) and subsequent estimated incidence of mastitis (29%) was higher than in other regions (ranging from 21% to 24%), which may explain the high proportion of first lactation animals as farms try to reduce SSC and mastitis levels. Pritchard, Coffey, Mrode, and Wall (2012) found that the coefficients of genetic variation for SCC and calving interval in the recorded UK dairy population are both low at 3% compared to moderately heritable milk production traits ranging from 11% to 13%, where genetic gains are more achievable. Regional differences in biological traits would support the need for customized and tailored selection indices for livestock, where producers create economic index weights specific to their farm circumstances. Such customized selection indices would seem appropriate for health and fertility traits with low heritability, and given their association with reductions in emissions intensity (Cottle & Coffey, 2013). Therefore, improved awareness or tools to enhance monitoring may help reduce these health and fertility issues. By reducing the risks associated with poor reproductive and milking performance and the incidence of mastitis the number of cows culled for management rather than involuntary reasons can be increased. Management and breeding policies should be directed towards not only increasing milk yield but decreasing the causes of involuntary culling to allow cows to reach their mature and optimum production of three to four lactations (Eggar-Danner et al., 2015; Rogers, van Arendonk, & McDaniel, 1988). Furthermore,

TABLE 6 Average change in profit (EV) due to a single unit increase in biological traits for the average herd in England, Scotland, Wales, and Northern Ireland

		EV (£/cow)			
Trait	**Units**	**England**	**Scotland**	**Wales**	**NI**
Milk volume	Liters	−0.04	−0.04	−0.04	−0.04
Milk fat yield	kg	2.85	2.83	2.72	2.70
Milk protein yield	kg	3.33	3.31	3.20	3.18
Survival	%	13.53	14.00	13.80	14.10
Somatic cell count	‘000 cells/ml	−0.28	−0.25	−0.24	−0.20
Mastitis	%	−1.83	−1.65	−1.58	−1.37
Calving interval	days	−2.78	−2.86	−2.80	−2.82
Methane	kg	−1.73	−1.77	−1.74	−1.75

TABLE 7 Average change in emission intensity (CO_2-eq.) per kilogram milk solids and per cow due to a single unit increase in biological traits for the average herd in England, Scotland, Wales, and Northern Ireland

		CO_2-eq. (kg per cow)				CO_2-eq. (g/kg MS)			
Trait	**Units**	**England**	**Scotland**	**Wales**	**NI**	**England**	**Scotland**	**Wales**	**NI**
Milk volume	Liters	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Milk fat yield	kg	5.8	5.8	5.9	5.9	−16.4	−16.6	−17.7	−17.5
Milk protein yield	kg	1.2	1.2	1.3	1.2	−23.5	−23.6	−25.3	−24.9
Survival	%	−48.7	−51.4	−51.6	−53.1	−91.1	−92.7	−97.9	−98.3
Somatic cell count	‘000 cells/ml	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1
Mastitis	%	0.8	0.7	0.7	0.6	1.3	1.1	1.2	0.9
Calving interval	days	14.9	15.3	14.7	15.0	23.1	23.4	23.7	23.9
Methane	kg	48.5	49.8	48.9	49.3	75.0	76.1	78.8	78.5

maintaining healthy and fertile cows can offer better feed and nutrient utilization with savings in GHG emissions per unit product (Garnsworthy, 2004), particularly later in life (Bell et al., 2011).

3.1 | Economic and emission intensity values

Of the eight biological traits assessed a desirable increase in economic value and potential to increase profit (Table 6) and reduce CO_2-eq. emissions per cow and per unit milk solids (Table 7) were associated with an increase in survival, and decrease in milk volume, SCC, mastitis incidence, calving interval, and CH_4 emissions. The economic values for milk production traits were similar for England and Scotland, and about 4%–5% lower for Wales and Northern Ireland for milk fat and protein yield. England had considerably higher economic values (between 10% and 30%) and emission intensity values (between 11% and 37%) for SCC and mastitis incidence than other regions, due to lost milk production and the higher gross margin (Table 5). Otherwise, overall there were only slight differences in economic values for individual traits between regions studied.

Of the traits assessed, a one percent increase in survival had the highest economic value across regions of about £14 per cow, as well as reducing CO_2-eq. emissions per cow (ranging from −48 to −53 kg) and per unit milk solids (ranging from −91 to −98 g/kg). A unit reduction in enteric CH_4 would also notably reduce CO_2-eq. emissions per cow (ranging from −48 to −50 kg) and per unit milk solids (ranging from −75 to −79 g/kg), if selection for lower emitters was possible commercially. For a trait such as enteric methane, which is a loss of dietary energy as gas, to be included in a multi-trait genetic and economic selection index that includes production and fitness traits would require phenotypic and genetic components for enteric methane, its correlation with other traits under selection and its economic value, as derived in the current study. Quantifying enteric methane emissions from individual animals on commercial farms is possible using a mobile gas analyzer while cows are being milked (Garnsworthy, Craigon, Hernandez-Medrano, & Saunders, 2012; Lassen, Løvendahl, & Madsen, 2012). Estimated CH_4 emissions per lactation were higher for the average Scottish herd (257 kg) and similar for an average herd in other regions studied (249–250 kg, from Table 1 and including contribution from herd replacements), which reflected the level of milk production, dry matter intake, and longer calving interval of cows in Scotland. The emissions of N_2O per lactation were similar across regions studied at about 11 kg. Estimated emissions for CH_4 and N_2O were higher than in the UK GHG inventory. Data in this study were from recorded cows, which are typically selected for improved production. This is the first study to explore regional differences in productivity and emission intensity of herds in the UK. While the results of the current study are consistent with detailed dairy herd experiments (Bell et al., 2011), the use of data from the national dairy cow population allows full expression of survival, and ultimately the impact of poor health and fertility.

4 | CONCLUSIONS

This study found regional differences in health (SCC and mastitis) and fertility (calving intervals) performance for dairy cows. Ultimately poor health and fertility impacts on the average lifespan of cows. In all regions studied, improving the health and fertility of cows leading to increased overall survival, will have a significant impact on increasing the profitability and reducing the emissions intensity per cow and per unit milk solids as more cows reach their mature productivity. The average herd in Scotland produced more milk but had a longer calving interval, which is an indicator of poor fertility. In comparison, the average herd in Northern Ireland produced less milk and had a shorter calving interval, but was associated with the highest SCC/mastitis. Resources such as feed inputs as forage and concentrate will remain the biggest input cost for modern dairy systems across the UK, with the potential to improve resource efficiency and increase profits. Once selection on enteric CH_4 emissions per cow becomes available, the economic values derived in this study could be used in an economic genetic selection index to help to increase farm productivity, profitability, and reduce the nutrient losses associated with milk production. This study provides a framework that can be customized for individual herds to allow assessment of resilience and resource efficiency of milk production not only in the UK but for comparison with international dairy systems.

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CONFLICT OF INTEREST

None declared.

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APPENDIX 1

TABLE A1 Assumed percentage of manure produced by management system for a herd replacement and lactating cow for an average system in England, Scotland, Wales, and Northern Ireland, 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 A2 Assumed average prevalence, incidence, treatments and input costs associated with health problems for UK dairy systems from Bell, Pryce et al. (2016)

		Mastitis				Lameness					Milk fever				Assisted birth	
		Clinical				Clinical										
	Units	Severe	Mild	Fatal	Subclinical	Digital	Interdigital	Sole ulcer	Uterine discharge	Retained placenta	Severe	Mild	Fatal	Oestrus not observed	Farm	Vet
Prevalence		0.15	0.84	0.01		0.68	0.32				0.05	0.87	0.08		0.82	0.18
Incidence		0.25	0.12	0.26	0.36	0.15	0.07	0.09			0.33	0.10				
Treatments		1.4	1.4	1	0	1.4	1.4	1.4	1.4	1	1	1	1	1.4	1	1
Herdsman's time	Minutes	30	15	0	0	180	60	300	0	0.0	60	60	60	0	60	60
Vet visit	Minutes	50	0	50	0	15	12	20	0	0.0	30	0	53	5	0	60
Discarded milk	No. days	9	7	0	0	7	5	6	0	0	0	0	0	0	0	0
Proportion of milk yield reduced		0.041	0.023	0.000	0.023	0.035	0.02	0.055	0.031	0.040	0.052	0.021	0	0	0	0.011
Medicine cost per treatment	£	40.0	5.6	40.0	0	12.9	11.3	12.0	10.8	6.3	8.0	5.0	18.0	5.3	0	0

Graphical Abstract

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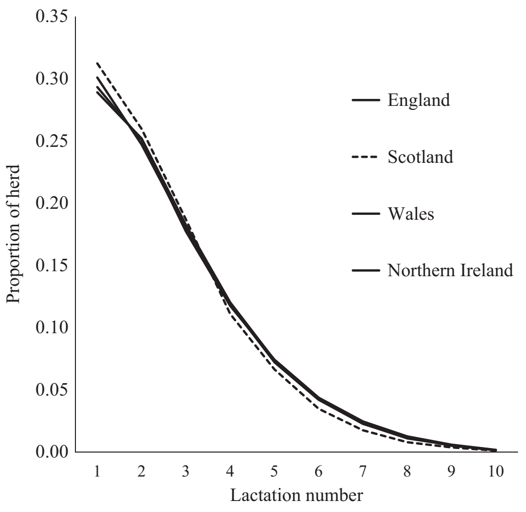

A method was presented for assessing regional and potential genotype × environment effects associated with forage-based dairy herds. Results would help improve the resilience and resource efficiency of milk supplies.