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Selecting the 'Sustainable' Cow Using a Customized Breeding Index: Case Study on a Commercial UK Dairy Herd

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Abstract: The aim of the current study was to investigate using a customized profit and carbon total merit index to identify sustainable milking cows and herd replacements within a commercial dairy herd. Balancing the economic, social and environmental aspects of milk production has gained interest given the increasing global demand for milk products. Furthermore, a farm-level customized breeding index with farm-derived weightings for biological traits would incorporate the effect of the farm environment. This study used a Markov chain approach to model a commercial dairy herd in the UK between the years 2017 and 2022. Production, financial, genetic and nutritional data for the herd were used as input data. The model derived the economic (GBP per unit) and carbon values (kilograms CO_2-eq. emissions per unit) for a single phenotypic increase in milk volume, milk fat yield, milk protein yield, somatic cell count, calving interval and lifespan, which were used in a profit and carbon index. The study proposed a methodology for selecting individual milking cows and herd replacements based on their potential to increase herd profitability and reduce carbon emissions as a means to identify more sustainable animals for a given farm environment. Of the 370 cows and herd replacements studied, 76% were classified as sustainable with a desirable increase in profit and reduction in carbon emissions. Customized breeding indices with trait weightings derived from the farm environment and selecting individual animals on economic and carbon metrics will bring permanent and cumulative improvements to the sustainability of milk production with appropriate nutrition and management. The approach used can be applied to any commercial farm to select animals that are more sustainable.

Keywords: dairy systems; biological traits; profit; greenhouse gas emissions

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1. Introduction

Global milk production and the number of milking cows are expected to keep increasing with the continued demand for dairy products [1]. About two-thirds of the carbon footprint of fresh milk is associated with the animal in the form of enteric and manure methane [1]. Therefore, the mitigation of greenhouse gas emissions is a priority if we are to achieve net zero targets in the future. In the UK, the emissions per unit of milk produced by dairy cows has been reducing by about 1% per annum over the last few decades with improved efficiencies, primarily due to better genetic selection and nutrition. However, the emissions per cow are estimated to increase by 1.0% per annum due to increased production [2]. The production efficiencies per unit product have been achieved by increasing productivity and gross efficiency (i.e., the ratio of yield of milk to resource input) with a dilution in the maintenance cost of animals in the system and decreasing the number of animals needed to produce the same amount of product [3,4]. Previous studies have highlighted that sustainable livestock breeding should aim to increase productivity while reducing negative environmental effects and improving livestock welfare [5,6]. Furthermore, Richardson et al. [7] identified that the use of genetic selection indexes should be explored further to reduce carbon emissions from livestock.

Given that genetic selection is permanent and cumulative with time, it is recognized as a cost-effective option for mitigating greenhouse gas emissions from livestock production [3]. However, the balance between productivity and resource efficiency has been a challenge for decades [8–10]. Genetic selection in livestock, such as dairy cows, has increasingly relied on a balance between the selection of more heritable production traits (e.g., kilograms milk, kilograms fat and protein) given their market value and fewer heritable fitness traits (e.g., lameness, mastitis, fertility and lifespan), which have welfare implications. The selection of dairy cows based on health, fertility and overall survival has been found to bring profitable reductions in the carbon footprint of milk with improved resource efficiency [2,11], which are all important social aspects for consumer confidence in livestock farming. Therefore, with more emphasis on fitness rather than production traits, the health and fertility of dairy cows is expected to improve, along with the carbon footprint of milk production. For this very reason, several countries (France, Italy, Germany, Switzerland, Belgium, Australia, the United States, the UK, Nordic countries, Ireland and The Netherlands) put more emphasis on fitness traits (>50% weighting) than milk production traits (milk, fat and protein yield) in their national breeding programmes [12]. In addition to these changes, breeding programmes are not only focused on economics but also health and environmental objectives. The use of a customized selection index, where a producer creates economic or other weights tailored to the farm environment, rather than the use of a nationally-derived breeding index and weightings (such as the economic Profitable Lifetime Index for dairy cows in the UK), may be more appropriate for traits associated with health and environmental goals [10].

The objective of the current study was to investigate the use of a customized profit and carbon total merit index to identify sustainable milking cows and herd replacements within a commercial dairy herd.

2. Materials and Methods

2.1. Data

Average production records between the years 2017 and 2022 were obtained for the Hartpury University Dairy herd, which is a commercially run and milk-recorded herd in the UK (Table 1). The herd consisted predominantly of autumn calving Holstein Friesian cattle with 60 one-year-old heifers, 72 first-lactation heifers and 238 older milking cows (up to eight lactations). The production (Table 1), financial, genetic and nutritional data for the herd and herd replacements were obtained.

Table 1. Average production values per lactation.

Trait	Units	Value
Milk volume	kg	8909
Milk fat yield	kg	347
Milk protein yield	kg	285
Lifespan	lactations	2.2
Somatic cell count	'000 cells/mL	129
Calving interval	days	368
Enteric CH_4 [1]	kg	146
Manure CH_4	kg	55
Manure N_2O [2]	kg	7
CO_2 equivalent emissions	tonnes	7.3

[1] Enteric CH_4 emissions per kg dry matter (DM) intake 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. [2] Direct and indirect N_2O emissions from stored manure and application of faeces, urine and manure and land applications of manure (from leaching and atmospheric deposition of nitrogen from NOx and NH_3) as used by the National GHG Inventory for agriculture in the UK.

The herd income and variable costs (Table 2) were used to derive the gross profit or loss per cow in a partial budget.

Table 2. Income and output costs (GBP) calculated for the herd per cow.

	Value
Income	GBP
Milk sales [1]	3029.24
Calves [2]	66.97
Culls [3]	141.70
Less	
Replacements [4]	877.70
Total Output	2013.43
Variable costs	
Feed	1298.51
Dairy supplies [5]	412.93
Health problems	183.01
Fertility	26.48
Total variable costs	1920.93
Gross Margin	439.28

[1] The average milk price was 34 p/L. [2] Average calf value of GBP 2.50 per kilogram body weight. [3] Average cull cow value of GBP 0.50 per kilogram body weight. [4] Average herd replacement cost of GBP 2.20 per kilogram body weight. [5] Average cost of GBP 0.05 per litre milk for recording, parlour consumables and sundries.

The predicted transmitting abilities (PTA) for each animal were calculated using the most recent genetic evaluations from August 2022 (Table 3). The PTA represents a prediction of the increased or reduced unit change in a trait that a cow will transmit to their progeny relative to the national average PTA of zero for the same month. The herd represented a wide range of positive and negative PTAs for production (milk volume, milk fat and milk protein) and fitness (somatic cell count, lifespan and fertility) traits included in this study.

Table 3. Average (s.d.) predicted transmitting ability per animal.

Trait	Units	Average	Min	Max
Milk volume	kg	74 (254)	−619	684
Milk fat	kg	2.7 (11)	−27	30
Milk protein	kg	3.2 (7.9)	−20	20
Somatic cell count	%	−1.8 (6.6)	−20	15
Lifespan	days	52 (36)	−92	122
Fertility	days	3.2 (3.9)	−11	12

The diet for a herd replacement heifer and lactating cow contained pasture, grass silage and concentrate feed (Table 4).

Table 4. Content and composition of the diet of a heifer replacement and lactating cow.

Nutrient Content	Units	Replacement	Lactating Cow
Crude protein (CP)	g/kg DM	142	203
Neutral detergent fibre (NDF)	g/kg DM	483	367
Ether extract	g/kg DM	49	42
Ash	g/kg DM	78	67
Metabolisable energy (ME)	MJ/kg DM	10.6	12.2
Feeding level [1]		2.5	4.7
Digestible organic matter in dry matter (DOMD) [1]	g/kg DM	661	711
Organic matter digestibility (OMD) [1]	% of OM	71.7	76.2
Digestible CP [1]	g/kg DM	85	143
Methane [1]	g/kg DM	21.1	18.8

Table 4. *Cont.*

Nutrient Content	Units	Replacement	Lactating Cow
Composition			
Pasture	%	33	33
Conserved forage	%	50	32
Concentrate	%	17	35

[1] The DOMD was estimated from Wainman (1981) as: DOMD (g/kg DM) = 472.49 × ln(ME) − 437.69; % OMD = [DOMD/(1000 − 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)/1000] × ((1000 − 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) with the feeding level being estimated from metabolizable energy intake as multiples of maintenance energy required.

2.2. Modelled Current and Adjusted Herd

The production, financial and nutritional data for the herd were used as inputs for an existing bioeconomic model that describes the nutrient partitioning of a cow over its productive life using a Gompertz growth curve (growth rate of 0.0033 kg protein/day). For more detail, see Bell et al. [2,11].

The Markov chain stochastic framework describes the herd structure as 11 age groups including life prior to entering the herd and from lactations one to 10 to cover the likely lifespan of a milking cow. This approach allows for a change in lifespan and herd structure to be assessed. The herd is described as a vector of states (s) that cows occupy at a given point in time [13], and each age group was included in the current study. Briefly, the vector of states at time t is multiplied by a matrix of transition probabilities (s × s) to generate a vector of states at time t + 1. The probability of a cow surviving to the next lactation (from lactation n to n + 1 and from lactation 1 to n) was dependent on survival during the current lactation. The model allows herd level data to be combined and cow biological traits to be adjusted in order to test the effect of adjusting the animal traits of interest on the key production, environmental and economic metrics as described below. Replacements joined the herd at 741 days of age on average, and sexed semen was used to breed herd replacements.

2.3. Feed Intake and Nutritional Requirements

The energy requirements (of herd replacements and lactating cows) for maintenance, growth, pregnancy, activity and lactation (E_{total}) are assumed to be achieved, and feed intake is always sufficient to achieve energy requirements. The metabolizable 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 in the herd presented in Table 5 were based on average production data (Table 1).

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

Energy Requirement	Replacement	Lactating Cow
E_{maint}	50.9	25.7
E_p	15.3	0.1
E_l	24.6	0.3
E_{preg}	4.0	2.4
E_{act}	5.1	2.6
E_{lact}	0.0	68.9
Total (E_{total} MJ)	38,890	76,556

The average total ME (E_{total}) requirement for each age group was used to calculate the feed intake (kg DM) of an animal (Equation (1)):

$$\text{Feed intake (kg DM)} = E_{total} \times 1/(ME - 0.616 \times ECH_4 - 3.8/FE - 29.2 \times DCP/6.25) \quad (1)$$

where ME, ECH_4 and FE are the metabolizable, enteric CH_4 and faecal energy (all MJ kg^{-1} DM), respectively, and DCP is the digestible crude protein (kg/kg DM). The values of 0.616, 3.8 and 29.2 are the heat increments associated with fermentation, faeces and DCP.

The total DM intake multiplied by ME content (Table 4) and cost per unit ME of the diet allowed the cost of feed consumed by each age group to be estimated, with pasture costing GBP 0.003 per MJ ME, grass silage costing GBP 0.009 per MJ ME and concentrates costing GBP 0.026 per MJ ME).

2.4. Changes in Profit and Carbon Emissions

The main greenhouse gases included were enteric and manure CH_4 and direct and indirect N_2O emissions from stored manure and application of faeces, urine and manure and land applications of manure (from leaching and atmospheric deposition of nitrogen from NOx and NH_3) as used by the National GHG Inventory for agriculture in the UK [14]. The IPCC [15] Tier II methodology was used to estimate manure CH_4 and N_2O emissions (from N excretion) from storage, as well as manure on fields. The estimated amount of N excreted by the animal was modelled to partition into faeces (N intake − digested N intake) and urine (N intake − (N retained + N in faeces)). Undigested organic matter in the diet (1 − digestible organic matter kg/kg) was used to estimate the other volatile solids in the manure. Emissions were expressed as CO_2-eq. emissions per cow. 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 [15]. The loss of dietary energy as enteric CH_4 was calculated using Equation (2) by Bell et al. [16]:

$$\text{CH4 (g/kg DM intake)} = 0.046 \times \text{DOMD} - 0.113 \times \text{ether extract (both g/kg DM)} - 2.47 \times (\text{feeding level} - 1) \quad (2)$$

where DOMD is the digestible organic matter in the dry matter and the feeding level is the metabolizable energy intake as multiples of the maintenance energy requirements.

The economic value and emission intensity in kilograms of CO_2-eq. emissions per cow were calculated by a single unit increase in the following biological traits of interest: milk volume, fat yield, protein yield, somatic cell count, calving interval (fertility) and lifespan. Responses to changes are quantified by calculating differences between the current herd situation and an adjusted situation due to a single unit change in each trait.

3. Results and Discussion

The herd studied represented a typical UK dairy herd with summer grazing and supplementary feeding (conserved forage and concentrate) and winter housing on solely conserved forage and concentrate feed (Table 4). The milk volume (8909 kg), milk fat yield (347 kg) and milk protein yield (285 kg) per cow (Table 1) were similar to the production of the UK average herd (8965 kg, 358 kg and 290 kg, respectively), but the average age of cows was lower at 2.2 lactations compared to 2.9 for the average UK herd [2,17]. The average calving interval of 368 days reflected the seasonal calving pattern of the herd studied. In terms of the genetic background of the cows in the case study herd, the data represent the production and fitness traits with a similar magnitude of negative and positive values for PTAs. The traits included are commonly available from herd genetic evaluations and have importance when applying economic and carbon weightings to a total merit index [2]. When genomic predictions for efficiency traits such as feed intake and methane output become routinely available for dairy genetic evaluations, then these traits can be included given their importance with regard to herd profit and carbon emissions [18,19]. After a single unit increase in each trait for the modelled herd, the following economic (GBP/cow;

Equation (3)) and carbon (CO_2-eq./cow; Equation (4)) weightings were derived to obtain a profit and carbon index based on the following trait PTAs:

$$\text{Profit index (GBP per cow)} = -0.08 \times \text{milk volume PTA} + 3.24 \times \text{milk fat yield PTA} + 3.91 \times \text{milk protein yield PTA} - 1.50 \times \text{SCC PTA} + 3.61 \times \text{calving interval PTA} + 1.48 \times \text{lifespan PTA} \quad (3)$$

$$\text{Carbon index (GBP per cow)} = 0.12 \times \text{milk volume PTA} + 5.55 \times \text{milk fat yield PTA} + 1.04 \times \text{milk protein yield PTA} + 0.84 \times \text{SCC PTA} - 16.83 \times \text{calving interval PTA} - 3.65 \times \text{lifespan PTA} \quad (4)$$

After applying both the profit and carbon indices to the PTAs for the 370 cows and heifers in the herd studied, 76% of the animals were classified as sustainable with a positive profit and negative carbon indices values based on their genetic background (i.e., animals in the top left corner of Figure 1). Overall, the average profit index was GBP 102/cow and the average carbon index was −195 kg CO_2-eq./cow. The values derived using the profit index (Equation (3)) were highly correlated (r = 0.85) with the Profitable Lifetime Index values calculated viaq UK national genetic evaluations for the same cows in the current study. This similarity is largely due to both profit indices having 50% weighting on production traits and 50% on fitness traits, even though the Profitable Lifetime Index includes more biological traits. Traditional breeding indices aim to identify suitable females or sires for breeding replacements. Kelleher et al. [20] proposed a lifetime profit index (cow own worth, COW) to help identify the most profitable dairy cows in a herd to aid replacement management rather than engaging in selection based on their breeding potential. The COW index was based on the expected economic performance in current and future lactations with the total genetic merit (i.e., additive and nonadditive genetic merit) of the animal as well as both permanent and temporary (e.g., season of calving, parity) environmental effects. Higher ranking cows on the COW index were associated with more milk and milk solids and calved earlier than lower ranking cows. Dunne et al. [21] proposed a beef breeding index framework based on the future profit potential of female beef cattle with the aim of identifying animals for culling. The approach was a modified version of the index of Kelleher et al. [20] and included genetic and non-genetic effects associated with each female. van de Heide et al. [22] also proposed an approach using genomic breeding values and phenotypic information to predict dairy cattle survival. The authors found that combining genetic and phenotypic information resulted in better predictions of survival. The indices developed in the current study were also based on genetic and phenotypic cow performance over a lifetime and include the period prior to entering the milk herd. The selection of more sustainable herd replacements with both profit and carbon indices (Equations (3) and (4)) will enhance the cow health, fertility and lifespan in the herd, especially with 25% weighting on production and 75% on fitness traits in the carbon index. Ultimately, poor health and fertility impacts the lifespan of animals, which has great importance for the economic, environmental and social aspects associated with the way livestock systems are managed. The traits included in the profit and carbon indices in the current study were similar to the traits found to be independent of carbon emissions in milk volume, fat yield, protein yield, survival and feed saved [23].

Even though the study was conducted on a single herd, the animals were all managed within the same production system with detailed herd information. Notably, 77% of first lactation heifers, 70% of older milking cows and 100% of the one-year-old replacement heifers were classified as sustainable for the farm studied. As individual animal genetic evaluations and economic plus carbon emissions change with time, the rankings can be updated in time for breeding management. The animals identified as sustainable for the production system in the current study can be prioritised for future herd replacements when planning breeding. This information and the use of customised economic and carbon weightings provides a more targeted selection tool than a national breeding index. This was also noted by Kelleher et al. [20]. The more targeted and tailored selection of livestock on economic and resource efficiency metrics at the individual animal level should improve overall herd performance and the sustainability of milk production. Deriving emission intensity weightings for biological traits is becoming more common for national environmental index use [7,18] rather than solely focusing on economic values.

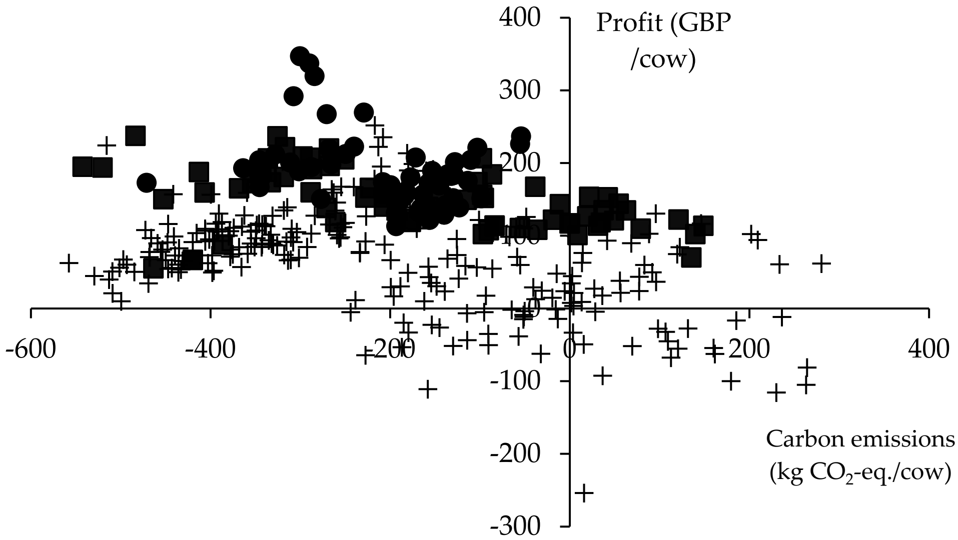

Figure 1. Profit (GBP/cow) and carbon (kg CO_2-eq./cow) index values calculated for milking cows (+), first lactation heifers (■) and one-year-old heifers (•) within the herd studied.

Since changes due to genetic selection are permanent and cumulative with time, it is considered a cost-effective strategy for future profitable reductions in carbon emissions per cow. However, for cows and heifers to achieve their genetic and sustainability potential, they would still require appropriate nutrition and management to meet their requirements. The current study applied a methodology that could be used at the farm level to select female and male animals that are suited to the farm environment, ultimately improving the production efficiency and environmental footprint. The more targeted selection of individual animals will be needed for livestock production systems to be more sustainable in the future. This work should be applied to more farms and national dairy cow populations to help farmers identify animals that are more sustainable.

4. Conclusions

In the present study, 76% of milking cows and heifer replacements studied were classified as sustainable, which was classified as an animal with a desirable positive profit and negative carbon indices values. Customized breeding indices with trait weightings derived for the farm environment and selecting individual animals based on economic and carbon metrics will bring permanent and cumulative improvements to the sustainability of milk production with appropriate nutrition and management. The approach used can be applied to any commercial farm to select animals that are more sustainable.

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