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Estimating the environmental impact of dairy cattle breeding programs through emission intensity

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ABSTRACT

A recently developed methodological approach for determining the greenhouse gas emissions impact of national breeding programs was applied to measure the effects of current and future breeding goals on the emission intensity (**EI**) of the Canadian dairy industry. Emission intensity is the ratio of greenhouse gas outputted in comparison to the product generated. Traits under investigation affected EI by either decreasing the direct emissions yield (i.e. increasing feed performance), changing herd structure (i.e. prolonging herd life) or through the dilution effect of increased production (i.e. increasing fat yield). The intensity value (**IV**) of each trait, defined as the change in emissions' intensity per unit change in each trait, was calculated for each of the investigated traits. The IV trend of these traits was compared for the current and prospective selection index, as well as for a system with and without quota (the supply management policy designed to prevent overproduction). The overall EI of the average genetic merit Canadian dairy herd per breeding female was 5.07 kg CO_2eq/kg protein equivalent output. The annual reduction in EI due to the improvement of production traits was −0.027, −0.018 and −0.006 for fat, protein and milk other solids, respectively. The functional traits, herd life and mastitis resistance, had more modest effects (−0.008 and −0.001, respectively). These results are consistent with international studies that identified traits related to production, survival, health and fertility as having the largest impact on the environmental footprint of dairy cattle. Overall, the dairy industry is becoming more efficient by reducing its EI through selection of environmentally favorable traits, with a 1% annual reduction of EI in Canada.

Implications

The dairy industry is scrutinized for the environmental impact associated with raising and maintaining cattle for milk production. Current selection indexes aim to improve the overall production efficiency of dairy cattle; however, the environmental impact of the genetic gain achieved by using a selection index has yet to be determined. By determining the environmental impact of selection for traits commonly included in selection indexes, future trends can be monitored to determine the effect of selection for specific index traits on the environment in the future, as well as enable long-term monitoring to be implemented at national and international levels.

Introduction

Global initiatives to lower greenhouse gas (**GHG**) emissions and improve environmental sustainability have dramatically increased in recent years. The agricultural industry has been targeted for its contribution to environmental degradation, and in particular, the environmental impact of raising and maintaining livestock has been scrutinized. Although dairy cattle represents only a moderate fraction of the total livestock sector, the increasing awareness of its environmental impact has placed pressure on industry partners to improve efficiency and increase the sustainability of animal production. As one of the 195 signatories of The Paris Agreement (Environment Canada, 2016), Canada is committed to decreasing national GHG emissions by 30% of 2005 levels by 2030. Of the 723 Mt of carbon dioxide equivalents (**CO_2eq**) of gross emission produced by Canada in 2015, 43.92 Mt was attributed to livestock production (Environment Canada, 2016).

Reducing net Canadian agricultural GHG emissions in the future is likely to be a significant challenge as an increasing amount of food is

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required to satisfy the growing Canadian and global demand. A more realistic expectation of the agricultural sector is to reduce the intensity of emissions for a given product over time. Therefore, Agriculture and Agri-Food Canada has set the goal of reducing the intensity of emissions for a given product over time. For this reason, we have focused on reducing emissions associated with the growth, transportation and processing of milk protein equivalents (Agriculture and Agri-Food Canada, 2016).

For animal breeding, prioritizing genetic traits based on gross outputs of methane (**CH_4**) is not optimal. Gross CH_4 is unfavorably associated with milk yield, and a targeted genetic decrease in gross CH_4 yield per cow may result in lower feed intake (Hegarty et al., 2007). This would almost certainly lower milk yield and also reduce biological efficiency, as feed consumed for simple maintenance would increase as a proportion of total DM intake (**DMI**).

The primary breed in the Canadian dairy industry is Holstein, monopolizing the industry by accounting for 93% of the population. Jersey (4%) and Ayrshire (2%) are the next predominant breeds with Brown Swiss, Guernsey, Milking Shorthorn and Canadienne combining to the remaining 1%. Hence, this paper will only consider the Holstein breed. Canada maintains a unique system of milk supply management, termed quota, controlling the national production of milk components to meet the demand of consumers. Of the 8.4 billion liters of milk produced in 2016, 33% was for Fluid Milk, 56% for Industrial Milk and 11% for Class 5 milk as defined under the harmonized milk classification system (Canadian Dairy Commission (CDC), 2020). This system introduces complexity as production is limited by the shares of supply management a producer owns.

Amer et al. (2018) recommended an approach in which the intensity of emissions per product unit of a system can be determined and utilized in breeding programs. Emission intensity (**EI**) is defined as the ratio of all GHG emissions produced by a system in comparison to the product output of the system. Emission intensity determines the favorable trends to lower emissions per unit output, therefore accounting for improvements in overall system efficiency. Over the past 20 years, the Canadian dairy industry has become more efficient through the selection of genetically superior animals, as shown through the decreasing number of dairy cattle in Canada and the increased volume of milk production (Canadian Dairy Information Center, 2017). This has resulted in lower emissions produced per unit of marketable product. Current traits within Canada's main selection index (Lifetime Performance Index; **LPI**; Canadian Dairy Network, 2017) can be assessed to determine the effect they will have on either GHG production or product output. The objective of this paper is to determine the independent, trait-specific effects of current and future selection strategies on the EI of the Canadian dairy industry.

Materials and methods

Emission intensity values (**IV**) were determined for the Canadian dairy herd of average genetic merit per breeding animal. The independent impact of each trait included in the national index was evaluated for its effect on the system when all other traits were held constant and termed IV. A total of four scenarios were investigated. In scenario 1, traits included in the current index were investigated. In scenario 2, we investigated traits expected to be included in a prospective index which includes total feed intake (**TFI**) in addition to all current traits. The purpose of scenario 2 was to show how inclusion of TFI in the breeding objective changes the calculations to obtain IV for energy sink traits such as milk production. Both scenarios were further compared in the case of presence or absence of a supply management system to investigate a total of four scenarios. The Canadian dairy industry operates under a complex supply management system based on the allocation of quota to producers, expressed in kg of butterfat. This system avoids domestic surpluses and shortages by managing production levels to coincide with forecast consumer demands, with kg of butterfat as the limiting factor (Canadian Dairy Commission (CDC), 2020).

Emission intensity of Canadian dairy system

The approach used to calculate the EI of the Canadian dairy system was based on the framework methodology described by Amer et al. (2018). In the current study, GHG emissions were calculated in terms of CH_4 production expressed in CO_2eq per unit of protein equivalents. Emission intensity, which applies to all scenarios, was calculated as (Amer et al., 2018):

$$EI = \frac{\sum_{i=1}^{c} \varepsilon_i n_i}{\sum_{j=1}^{p} y_j n_j k_j} \tag{1}$$

where ε is the emissions for a fixed time period (average calving interval of 419 days was used in the current study) across c different animal classes (replacement heifer and weighted subsequent lactations and dry periods based on survival rate from first lactation to life stage, indexed i), n_i is the number of animals in each class expressed per breeding female, y is the product output generated across p different product categories, within the fixed time period, n_j is the number of animals on average per breeding female producing the jth product and k are proportionality coefficients that convert the jth product into milk protein equivalents (Table 1). The numerator and denominator of Eq. (1) sum to calculate the level of emission yield and product output, respectively.

For the current study, the emissions of replacements and breeding cows were considered to contribute to the total GHG output. Emissions were calculated based on the amount of emissions associated with the total DMI of the animal class (Richardson et al., 2019). In this study, the average daily DMI for a replacement and breeding cow was calculated and then cumulated based on the Canadian average for number of days in each animal class. The number of replacements per breeding female was determined to be 0.38 as this is the average Canadian replacement rate (Table 2). Total product yield was calculated by determining the average yearly production of each output converted to protein equivalents per breeding female (Table 2). Products considered in the current study were milk and its components (protein yield, fat yield and lactose yield); however, it is possible to consider other product outputs such as meat production from veal calves and cull animals.

Table 1
Constants and conversion factors used in emission intensity and intensity value calculations for dairy cattle.

Constants	Value
CH_4 yield, g/kg DMI[1]	17.00
CH_4 global warming potential, GWP	25.00
Milk component value, CAD$[2]	
Fat, kg	10.60
Protein, kg	7.960
Lactose, kg	1.155
Standardization ratios[3]	
k, fat	1.330
k, lactose	0.145
k, milk	0.007
Feed required/kg milk component[4]	
Fat, kg DM	6.00
Protein, kg DM	3.70
Lactose, kg DM	2.60

[1] DMI is DM intake.
[2] Producer Milk Statement (Dairy Farmers of Ontario, 2017) in Canadian dollars (CAD$).
[3] k is the protein equivalent output standardization ratio used to convert milk, fat and lactose yields into measurements of protein equivalents.
[4] Values obtained from Amer et al. (2018).

Table 2
Constants based on the Canadian dairy cattle herd of average genetic merit used to calculate product and emissions outputs.

Constants	Cow	Replacement
Feed intake, kg DM[1]	8 660.40	5 932.17
Number of replacements per breeding female[2]	1.00	0.38
Average 305-d milk yield, kg[1]	10 102.00	–
Protein, %[1]	3.19	–
Fat, %[1]	3.87	–
Lactose, %[1]	4.90	–

[1] Values obtained from Richardson et al. (2019).
[2] Based on data provided by Canadian Dairy Network, G. Kistemaker (Guelph, ON, personal communication).

The change in EI that arises from a 1-unit change in a genetically controlled trait*x* has been derived by taking the first partial derivative of Eq. (1) with respect to genetic merit for a trait *x* (Amer et al., 2018). These values are referred to as GHG IV. This was done via a special case of the Amer et al.'s (2018) method, whereby the equation was remodeled to more appropriately represent the dairy production system, in which the majority of births produce a single offspring of limited marginal value (CAD$/kg body weight).

$$IV = \frac{\delta EI}{\delta x} = \frac{1}{\sum y^{\bar{g}}}\left[\sum_i \frac{\delta \varepsilon_i(x)}{\delta x} n_i^{\bar{g}} + \sum_i \frac{\delta n_i(x)}{\delta x}\varepsilon_i^{\bar{g}} - EI^{\bar{g}}\left(\sum_j \frac{\delta y_j(x)}{\delta x} n_i^{\bar{g}} k_j\right)\right] \quad (2)$$

where $\Sigma y^{\bar{g}}$ is the total system output calculated as the sum over multiple outputs *y* (indexed j) converted to protein equivalents using the scaling factor k_j for an animal of an average level of genetic merit $\bar{g}$ and $EI^{\bar{g}}$ is the total GHG emissions per breeding female expressed as CO_2eq of output at an average level of genetic merit. The first term in the brackets accounts for the change in direct emissions, ε_i, per change in the index trait *x* with a weighting to account for the number $n_i^{\bar{g}}$ of animals in class i per breeding female. The second term represents a change in the number of animals, weighted in terms of breeding females, per change in index trait *x*. The final term represents a dilution effect due to a change in product output, y_i, of animals in class i, per unit change in index traits *x*, expressed as protein equivalents using different relative product values, *k*, for each product output.

Intensity values for each trait were calculated for a system with and without supply management. For a system without quota, IV were calculated for a fixed number of cows, while for a system with quota, the system had a fixed product output (fat).

Standardization of output ratios

The amount of total product output was calculated in terms of protein equivalents; therefore, standardization factors were calculated to convert milk, fat and lactose yields into measurements of protein equivalents. Milk volume, fat, lactose and protein conversion factors were determined based on the Canadian quota payment system. While the quota system is allocated on kg of fat production, there is also a solids-not-fat to butterfat ratio requirement at each bulk tank collection. This means that there is no advantage from long-term selection for low fat percentage in order to maintain revenue from other solids at a given fat production. Effectively, milk payment is based on CAD$/kg for both fat and protein, the effective values of which are comparable in magnitude. There is also a payment for lactose and other solids of CAD $1.62/kg. At 5.8% non-fat and non-protein solids, payment for lactose and other solids equates to 1.62 × 0.058 = CAD$0.094/l of milk. However, transport charges of CAD$0.027/l are deducted, implying a net price per liter of CAD$0.094 − CAD$0.027 = CAD$0.067/l, which when expressed back to milk solids gives 0.067/0.058 = CAD$1.155/kg lactose. This resulted in the standardization values for milk components shown in Table 1, where assumptions were based on the previous 5 years of component value explanation of the Producer Milk Statement (Dairy Farmers of Ontario, 2017). While other producer payments such as administration, research and promotion are applied based on milk volume in the Canadian milk pricing system, we assume that these do not reflect a true difference in the value of lactose relative to fat and protein. The percent of fat, protein and lactose in milk was assumed to be constant at the national 5-year annual averages of 3.87%, 3.19% and 4.90%, respectively, across generations and production systems for all calculations. Thus, the protein equivalent output standardization ratios, k, were calculated (taking values from Table 1) for fat as 10.60/7.96 = 1.33 and for lactose to be 1.155/7.96 = 0.145. Milk had its value ratio relative to protein based on lactose and was calculated as 0.145 * 4.9% = 0.007, termed milk other solids (**MOS**).

Calculated gross emissions from feed intake

Methane yield varies among animal classes, due to the variation observed in animal age and weight, in addition to the differences in feed quality, quantity and feeding systems (Quinton et al., 2018). The conversion of CH_4 emissions to CO_2eq in dairy cattle has been calculated in various studies from CH_4 production using the ratio of CH_4 to CO_2eq (O'Mara, 2006; Wall et al., 2010). For the current study, the output of CO_2eq from feed intake in dairy cattle was estimated to be 0.425 kg CO_2eq/kg DM as per Richardson et al. (2019). This constant was calculated using the gross CH_4 production of 0.017 kg CH_4/kg DMI obtained from Canadian Research Facility, D. Hailemarium (Alberta, ON, personal communication) and a Global Warming Potential (**GWP**) conversion ratio of 25:1 for CH_4 to CO_2eq, assuming a linear relationship and no variation between animals or type of diet.

Selection indexes

The Canadian dairy industry has developed two indexes for the genetic evaluation of dairy cattle, LPI and Pro$. The LPI is composed of three sub-index components: production, durability, and health and fertility. The production component (40% relative emphasis) is based on fat and protein traits; the durability component (40%) on herd life, mammary system, feet and legs, and dairy strength; and the health and fertility component (20%) on daughter fertility and mastitis resistance (Canadian Dairy Network, 2019). Pro$ is an economic-based index, in which the profit response of each trait is weighted based on its economic significance to the producers (Van Doormaal et al., 2015). In addition to traits mentioned previously, digital dermatitis, metabolic disease resistance and feed efficiency will soon be included in the national genetic evaluation indexes. Therefore, the EI value of these traits was also estimated.

Calculating intensity values for index traits in a non-quota system

Out of all of the traits currently under genetic evaluation in Canada, feed efficiency, MOS yield, protein, fat, herd life and mastitis resistance are the only traits with a direct impact on EI and are independent from all other index traits.

Feed efficiency

It was previously determined by Richardson et al. (2019) that for every 1-unit decrease in estimated breeding value (**EBV**) for a Feed Performance (**FP**) trait, there would be a 3.23 kg reduction in unnecessary feed used. The FP trait is defined as a 1 kg increase in more efficiently used feed by a first parity lactating cow and targets the feed wasted on inefficient digestion, metabolism and maintenance. Each kg of feed consumed is associated with 0.425 kg of CO_2eq produced (Richardson et al., 2019). Therefore, emissions change per unit change in FP EBV was 1.37kg CO_2eq. Calculations for feed efficiency are included for scenario 1 calculations only because FP is defined so as to be adjusted for key energy sink traits, and so the feed consumption penalty on IVs must be incorporated directly into the IV calculations for these energy sink traits.

Production traits

Genetic improvement of production traits causes dual effects on EI. The first is an increase in emissions output, as more feed is required to sustain the increase in product output. The second is that the additional product output dilutes the fixed emissions to an extent which more than offsets the increase in emissions associated with greater feed requirements. Constants used to calculate these effects are presented in Tables **1** and **2**. Calculations of CO_2eq output and protein equivalents for each production traits were as follows.

Milk

To avoid double counting for an increase in protein and fat when considering the effect on the emissions and product for an increase in milk EBV, only lactose was considered. Therefore, the contribution to EI due to milk is represented by the MOS trait, which includes all milk solids other than fat and protein and is valued based primarily on lactose. The amount of CO_2eq/ kg lactose was calculated as the emissions produced due to the additional DMI required to produce 1 kg of lactose (2.6 kg DM/kg lactose * 0.425 CO_2eq/kg DM = 1.105 kg CO_2eq/kg lactose). For an additional 1 kg of milk, 0.049 kg of lactose × 1.105 kg CO_2eq/kg lactose = 0.054 kg CO_2eq is produced. However, additional lactose, through its association with milk volume, generates some additional output value. This output value slightly dilutes emissions per cow by the generation of 0.007 kg protein equivalent (0.049 kg lactose per liter × 0.145).

Protein

The amount of CO_2eq/kg protein was calculated as the emissions produced due to the additional DMI required to produce 1 kg of protein (3.7 kg DM/kg protein * 0.425 CO_2eq/kg DM). For an additional 1 kg of protein EBV, 1.57 kg CO_2eq is produced. This is diluted by the generation of 1 kg protein.

Fat

The amount of CO_2eq/kg fat was calculated as the emissions produced due to the additional DMI required to produce 1 kg of fat (6 kg DMI/kg fat * 0.425 CO_2eq/kg DMI). For an additional 1 kg of fat, 2.55 kg CO_2eq is produced. This is diluted by the generation of 1.33 kg protein equivalents (1 kg fat × 1.33).

Functional traits

Herd life

A change in herd life EBV affects the equation in two ways as follows: 1) increasing the longevity of the herd means less replacements to rear and 2) an increased milk yield due to fewer first lactation animals in the herd. Therefore, for every 1-unit increase in herd life, 0.32% less replacements are required × 2 533.67 kg CO_2eq per reared replacement = 7.63 kg less CO_2eq produced. There is less of a requirement for replacements, so the average age of the herd will increase. Later, parity animals produce more compared to first parity animals; therefore, the average milk yield per cow from a herd genetically superior by 1 herd life EBV is 6.01 kg milk production. This is then converted to 0.544 kg protein equivalents via the conversion factor (0.091 kg protein equivalents/kg milk).

Mastitis resistance

The effect of mastitis resistance on EI was based on the volume of milk loss due to discarded milk. It is recognized that additional milk loss may occur following a clinical mastitis infection for the remainder of the lactation; however, it is assumed that this is accounted for in the test-day model EBV for milk. The average cow is removed from the tank for 7 days (3 days treatment + 4 days drug withdrawal) with an average production per day of 33.21 kg milk based on 3-year historic data provided by CDN (G. Kistemaker, Guelph, ON, personal communication). Therefore, the total milk loss due to discarded milk is 231.8 kg/case. The average number of cases per clinical mastitis incident is 1.4 (Lago et al., 2011). A weighted average over all three lactations was calculated to determine the reduction in clinical mastitis cases by 1-unit increase in EBV (0.0056). The effect on product output is 231.8 kg/case × 1.4 cases/clinical mastitis incident × 0.0056 reduction in incident/mastitis resistance EBV × 0.091 kg protein equivalents/kg milk = 0.165 kg protein.

Impact of accounting for the supply management system (scenario1b and 2b)

The Canadian supply management system constrains the weight of milk fat production per herd; therefore, there can be no output gained from increasing the fat production of animals with the goal of reducing the EI of the system. However, genetic improvements made through the fat EBV can be expressed in terms of altering EI through herd structure, as less animals are required to meet the quota requirements for fat. Every 1 kg increase in fat EBV necessitates 0.26% less animals in order to stay below fat quota (i.e. 1 kg quota/ average cow fat yield); therefore, a 1 kg gain in fat can be expressed as a decrease of 11.52 kg CO_2eq output via herd structure (4 471.49 kg CO_2eq/cow * 0.26% fewer cows in the herd). Although reducing herd size has a positive effect on emissions output, there is an unfavorable change in herd protein and lactose output because of the fewer producing animals required to fill the fat quota. Thus, there is a reduction in the amount of protein equivalents produced when the fat EBV is increased by 1 unit. The amount of product output loss is equivalent to the total protein equivalent output which would have been generated by the 0.26% less animals in terms of protein and lactose, totaling to 1 kg protein equivalents (0.26% fewer animals * [322.25 kg protein + (494.99 kg lactose * 0.145)]). For all traits other than fat, IV are calculated identically to the situation without a quota constraint.

Genetic trends and trait standardization

To put into perspective the annual potential these traits have to reduce EI, IVs for each trait were multiplied by corresponding estimates of annual genetic gain (Table 3). The outcome represents the yearly decrease in EI expected for each trait independent of all other index traits. We subsequently refer to these as "IV trait trends" with the units of change in EI per change in trait unit per year ($\frac{\delta EI}{year}$). Some traits have significantly greater genetic improvements than others per year. For FP as defined by Richardson et al. (2019), a current genetic trend was not available. Three potential responses to selection were previously investigated to determine expected rates of genetic gain for the FP trait. In the previous study, it was assumed that a first parity lactating animal consumes 6863.45 kg of DM per lactation and that 40% of the total DMI in

Table 3
Trait annual genetic gain trends in dairy cattle.

Traits	Trait genetic gain/year (2011–2016)[1]
Total feed intake, kg DM	–
Milk, kg	120.60
Fat, kg	5.96
Protein, kg	4.80
Herd life	0.67
Mastitis resistance	0.49

[1] Provided by Canadian Dairy Network; L. Beavers (Guelph, ON, personal communication).

the first lactation would be targeted as inefficiently used feed for genetic improvement in FP based on the genetic variation in DMI. The three investigated responses to selection were a 0.25%, 0.5% and 1% annual improvement rate of the targeted inefficiently used feed. Therefore, a moderate genetic trend equivalent to a 0.5% reduction in total inefficient feed consumed by a first parity lactating cow per year of genetic gain was assumed in anticipation of the potential impacts of this new trait (Richardson et al., 2018). This hypothetical trend in the proposed FP trait was evaluated in the context of scenario 1 because the FP trait considers only feed intake after some yet to be determined adjustment for feed energy sinks such as milk yield, and so IV for the energy sink traits still need to be penalized for their associated feed requirements.

For functional traits, such as herd life and mastitis resistance, breeding values are presented as relative breeding values (**RBV**), with a mean of 100 and standard deviation of 5. In order to achieve greater biological meaning, these RBV were converted back to EBVs before calculating trait IV (Canadian Dairy Network, 2014).

To compare the IV of traits across countries and production systems, relative emphasis values were calculated. The values describe the percentage of the total effect that each trait has on improving EI and are calculated as follows.

$$\text{Relative emphasis}_i = \frac{IV_i \times SD_i}{\sum IV_i \times SD_i} * 100 \quad (3)$$

where IV_i is the intensity value and SD_i is the EBV standard deviation of each trait, i, evaluated for its effect on EI.

The percent annual reduction in EI due to the genetic improvement of each of the investigated traits for scenario 1 and 2 was calculated as follows.

$$\%\text{annual reduction}_i = \frac{IV_i \times GT_i}{EI^{\bar{g}}} \quad (4)$$

where GT_i is the annual genetic trend for trait i and all other variables are as described above.

This formula can be adjusted to determine the total improvement in EI achieved through genetic gain each year and is calculated as follows.

$$\text{Total annual\%reduction} = \frac{\sum IV_i \times GT_i}{EI^{\bar{g}}} \quad (5)$$

where variables are described as above.

Sensitivity analysis

A sensitivity analysis was conducted to investigate the effect of variations in milk component value, which effectively impacts protein equivalent standardization ratios, k, on EI and IV trait trends. In the sensitivity analysis, only fat and protein were considered as the value of these milk components constitutes the majority of the value in milk. The possible variation was tested under the assumption of a k standardization ratio for fat to protein of 0.95 and 1.70, representing an over and underestimation of the current k standardization ratio for fat of 1.33.

Results

Emissions output, production output and emission intensity

The total emissions output and product output ($\Sigma y^{\bar{g}}$) generated per breeding female in the allocated time period were determined to be 4 638.72 kg CO_2eq and 914.76 kg protein equivalents, respectively. Therefore, the EI value for the average Canadian dairy farm with average genetic merit is the ratio of these two values, equating to 5.07 kg CO_2eq/kg protein equivalents ($EI^{\bar{g}}$).

Trait intensity values

The IV $\left(\frac{\delta EI}{\delta x}\right)$ and IV trait trend $\left(\frac{\delta EI}{year}\right)$ calculated for each trait with notable effect on EI for scenarios 1 and 2 are presented in Tables 4 and 5, respectively.

Under scenario 1, where TFI is not a trait in its own right in the breeding objective, MOS had an unfavorable IV trait trend (IV * annual average genetic gain) of 0.002, with all other traits having a favorable IV and IV trait trend. Increased milk production inflates feed requirements to support the energy contained in milk lactose, while offering no dilution benefit through increased output. Intensity value trait trends for fat and protein (−0.027 and −0.018) suggesting that these production traits have the largest positive effect on EI. The functional traits follow with herd life and mastitis having an IV trait trend of −0.008 and −0.001, respectively. When evaluated with the restrictions of quota, the fat IV trait trend was reduced to −0.025 with all other traits remaining constant. Overall, through an accumulation of all IV traits trends, a 1% improvement in EI per annum is expected using scenario 1. This would increase to 1.5% if the hypothetical annual genetic trend of 0.5% of total inefficient feed could be achieved by including the proposed FP trait in the breeding objective.

Under scenario 2, where TFI is considered, investigated traits had a neutral or favorable IV, such that the economically desirable direction of genetic change also resulted in an improvement in EI. Fat had the greatest impact on EI with a IV trait trends of −0.044. Protein had the next largest IV trait trend of −0.027. Herd life and MOS had small favorable IV trait trend of −0.008 and −0.005, respectively. Of all of the traits considered, mastitis resistance had the lowest impact per year at

Table 4
Intensity value and intensity value trait trend for dairy cattle in scenario 1 (current index) with and without supply management.

Trait	Intensity value,[3] $\left(\frac{\delta EI}{\delta x}\right)$	Intensity value trait trend,[3] $\left(\frac{\delta EI}{year}\right)$
Total feed intake, kg DMI	0	–
Milk other solids (MOS),[1] kg	0.00002	0.002
Fat, kg[2]	−0.005	−0.027
Protein, kg	−0.004	−0.018
Herd life	−0.012	−0.008
Mastitis resistance	−0.001	−0.001

DMI = DM intake; EBV = Estimated breeding value.
[1] Milk Other Solids represents the effect of the milk EBV considering only lactose to avoid double counting for an increase in protein and fat.
[2] Values for fat within a quota system were −0.004 and −0.025 for intensity value (IV) and annual IV trait trend, respectively.
[3] δEI is the change in emission intensity and δx is the change in index trait.

Table 5
Intensity value and intensity value trait trend for dairy cattle in scenario 2 (current index plus TFI) with and without supply management.

Trait	Intensity value,[3] $\left(\frac{\delta EI}{\delta x}\right)$	Intensity value trait trend,[3] $\left(\frac{\delta EI}{year}\right)$
Total feed intake, kg DMI	−0.002	–
Milk other solids,[1] kg	−0.0001	−0.005
Fat, kg[2]	−0.007	−0.044
Protein, kg	−0.006	−0.027
Herd life	−0.012	−0.008
Mastitis resistance	−0.001	−0.001

TFI = total feed intake; DMI = DM intake; EBV = Estimated breeding value.
[1] Milk other solids represents the effect of the milk EBV considering only lactose to avoid double counting for an increase in protein and fat.
[2] Values for fat within a quota system were −0.004 and −0.042 for intensity value (IV) and annual IV trait trend, respectively.
[3] Where δEI is the change in emission intensity and δx is the change in index trait.

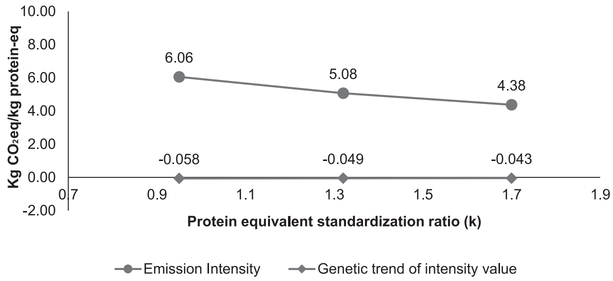

Fig. 1. Emission intensity (kg CO_2eq/kg protein equivalents; protein-eq) and intensity value trait trends (kg CO_2eq/kg protein equivalents per year) for dairy cattle under different protein equivalent standardization ratios for fat (k).

−0.001. Under a supply management system, all IV trait trends remained constant except for fat. The IV trait trend of fat was lowered to −0.042 when the restraints of a supply management system were applied. The IV for a TFI trait was determined to be −0.002.

Sensitivity analysis

The effects of changing milk component values and resulting k standardization ratio on EI and IV trait trends are presented in Fig. 1. The EI calculated under a k standardization ratio for fat of 0.95 and 1.70 was estimated to be 6.06 and 4.38 kg CO_2eq/kg protein equivalents, respectively. The emissions per kg of protein equivalents compared with the base estimation of EI (5.07 kg CO_2eq/kg protein equivalents) varied by only 0.003% when the value of the k standardization ratio for fat changed from 0.95 to 1.70.

Discussion

The effects of genetic trends and trait intensity values

The overall effect each trait has on EI is proportional to its IV and rate of genetic improvement. Although a trait may have a numerically large IV, genetic gains can potentially be more modest due to lower heritability estimates, modest index emphasis and because of a relatively recent introduction or understanding of the trait as a part of the genetic evaluation process. The response to selection on selection indices can therefore be minimal leading to a lower annual change in the trait's effect on EI. Herd life, for example, has a substantial IV, as it affects both product output and herd structure; however, this trait has much smaller genetic trend in comparison to fat and protein due to its lower relative response to selection, which results in the trait having a lower overall effect on total production system EI.

The combination of genetic trends with the IV estimates resulted in the re-ranking of trait effects on EI (Tables 4 and 5). Traits with higher accuracy of evaluation and/or emphasis within the selection index typically have greater rates of genetic gain observed each year, and the impact of differences in units of the different traits is eliminated. Production traits, for example, have been selected in dairy cattle for many generations and have considerable genetic variation which can be targeted to generate high levels of genetic gain each year. In comparison, mastitis resistance, which is a novel trait, has a lower heritability and possibly lower genetic variation and only modest index weighting, resulting in less genetic gain each year. Genomic selection will help to increase the genetic gain in traits with lower heritability estimates as genomic prediction accuracies improve over time due to the growth of larger training populations. Correlations between traits may also affect their rate of genetic improvement; therefore, traits that are favorably correlated will benefit from mutual genetic gain.

Inclusion of feed efficiency in index (future index trends)

The current national index had a general trend towards improving EI for most index traits, with the exception of MOS yield. Milk other solids yield had positive IV and IV trait trend, suggesting that genetic improvement for greater MOS production is not favorable. However, in the current model, MOS yield was investigated independently of fat and protein, and therefore, the product output from an increase in milk yield considers only the production of lactose and water. A positive focus on production of lactose and water would be economically inefficient, as the current multi-component payment system does not support increased fluid milk yield without proportional increases in components, and lactose comes with a non-trivial associated feed cost.

Under scenario 1, a hypothetical assumption was made that an additional 0.5% reduction in EI might be achieved annually due to the targeting of inefficient feed usage through FP trait. In scenario 2, a TFI trait was considered which required the reconsideration of emissions due to feed consumption in order to avoid double counting. Considering TFI in scenario 2 demonstrates that IVs are expected to change when varying definitions of feed efficiency traits are included in the index. This resulted in an adjustment of the IV and IV trait trends for the production traits. The IV for TFI (−0.002) was independent from all other traits under investigation. It is recognized that including TFI in the index may lower the selection emphasis placed on the other investigated index traits. However, as described by Smith et al. (1986), this should not significantly affect the efficiency of the index as all economically important trait is included with the appropriate direction of selection response. Therefore, analogous genetic improvements should be achieved.

Effect of quota on efficiency

In current and alternative index scenarios, when values are compared in a system with and without supply management, the IVs are only minimally affected. As quota places a restraint on the weight of fat production, it was expected that the fat IV would be affected. However, the results shown for the situations with and without a quota on fat are comparable and should not have an effect on the overall efficiency of the index. Smith et al. (1986) compared economic weights of traits based on variable systems with fixed output, output values, input and profit and showed that when the breeding focus is targeting efficiency, the economic weights would not vary according to which these effects were fixed. This is consistent with our consideration of the quota system, which fixes the output value of the fat production, and the non-quota system which is fixed per breeding female, where both produce almost identical trait IVs.

Sensitivity analysis

As demonstrated through the conducted sensitivity analysis, reasonable variation in the value of milk components has minimal effect on the annual reduction in EI due to genetic progress. Although differences were observed in EI at varying k standardization ratios for fat, once genetic trends for each index trait were accounted for, the actual variation in EI reduction between milk component values was minimal. Zhang et al. (2019) described the challenges associated with rapidly changing global market prices of milk components when estimating the environmental effect of selection indexes as the fat to protein ratio has drastically changed in recent years. However, due to the implemented quota system, the Canadian dairy industry is not impacted by the volatile global markets and milk value parameters may be confidently estimated (Dairy Farmers of Canada, 2017).

Additional index traits

Some additional traits investigated for their effect on EI were not included in the main results so as to avoid double counting of factors. For example, the effects of digital dermatitis are currently accounted for in the EBVs for milk production and herd life. Increased prevalence of hoof lesions decreases the locomotion of animals and consequently decreases milk production, as animals are less motivated to visit the feed bunk. It is assumed that for animals with scores above 3 on the locomotion scale, milk production decreases by 2% (Archer et al., 2010); however, this loss of milk in daughters of sires with a genetic predisposition to milk production affecting diseases should be captured in the test-day model milk EBV. Similarly, an increase in involuntary culling due to digital dermatitis would be captured by the herd life EBV. Therefore, the EI benefits which would be achieved by predictor traits are effectively captured by the weighting applied to mainstream traits already considered.

Effect of variable definitions of feed efficiency

For the purpose of the current study, our definition of the feed trait for scenario 2 was related to a TFI trait. Therefore, when evaluating a system where one trait is changing and all other traits are fixed, it is assumed that there is no additional feed consumed for an increase in one unit of product. Alternative measurements of feed efficiency that target genetic change in only a component of DMI, such as residual feed intake (**RFI**), might not account for the feed associated with additional changes in some other traits. In this case, there would be an intermediary between scenarios 1 and 2, which would depend on the definition of the RFI. For example, feed associated with milk production traits (milk, fat and protein) is usually adjusted out of RFI definitions and so their IV values should be taken from scenario 1 in this instance. The functional traits (herd life and mastitis resistance) would not be affected by this change in feed efficiency trait definition.

Comparison with other studies

Our study identified the production traits, fat (57% relative emphasis) and protein (35%), to have the largest effect on EI. This was followed by MOS (6%) and herd life (1%) with mastitis resistance having the lowest relative weighting (<1%).

In comparison, Bell et al. (2015) investigated EI in the UK using a bioeconomic model. This model identified RFI (i.e. feed efficiency) as the most prominent trait affecting EI, responsible for 36% of the total improvement in emissions footprint. Following was protein and fat with relative emphasis of 23% and 14%, respectively, which would increase to 31% and 19% if RFI was ignored. Notable additional effects were that of survival, milk volume and calving interval (12%, 9% and 5%, respectively). Milk volume and calving interval have an inverse relationship with EI, as a more negative value (shorter calving interval and decreased fluid milk) has a favorable outcome. As found in our study, Bell et al. (2011) suggested that an improvement in EI was associated with increasing longevity and lowering involuntary cull rate, both attributes of the herd life trait.

Similarly, the results obtained by Amer et al. (2018) for Irish cattle were comparable with those of our study, with protein and fat having the highest effects (54% and 11%, respectively) and survival and calving interval following (18% and 17%, respectively). Amer et al. (2018) calculated a much lower relative weighting for fat relative to protein than derived here, and so the dilution benefits of fat were much lower in their study. Similar trends were observed for other production and survival traits, which are comparable to Canadian production and herd life traits.

In agreement with our study, Pryce and Bell (2017) reported that fat (35%) had the largest effect on EI. "Feed Saved" (i.e. feed efficiency) had a lower relative emphasis (13%) than reported by Bell et al. (2015). Other notable effects included survival (11%) and calving interval (11%); however, milk (19%) and protein (10%) had contrasting relative emphasis to those reported in our study. These inconsistencies may be due to the different payment structures and trait models between production systems. The Canadian milk payment system places a higher value on fat (CAD$10.60/kg) than protein ($7.96/kg), as well as an additional value on milk (CAD$1.16/kg), compared to the world market and those reported by Pryce and Bell (2017) of AU$2.79/kg and AU$6.64/kg for fat and protein, respectively. Additionally, the Canadian genetic evaluation system uses a test-day model (Schaeffer et al., 2000). Therefore, large changes in milk production due to health events (i.e. mastitis) are captured in production traits EBVs, effectively increasing the IV of production traits and lowering the IV of functional traits.

The reported percent reductions in total EI per year achieved through genetic gain using the current index of 1% were similar to results shown in other studies. Amer et al. (2018) reported a 1% improvement per year in EI. Other studies present reductions in terms of total GHG emissions; however, these values are in comparable ranges of 1.0–2.6% (Bell et al., 2010; de Haas et al., 2011; Pryce and Bell, 2017).

Conclusion

This paper estimates the environmental effect of selecting cattle based on the current national Canadian dairy selection index, the LPI. Overall, the genetic gain achieved through selection on LPI for traits related to production, health and survival resulted in an 1% annual improvement in EI. Traits with independent impacts on EI included fat, protein, milk, herd life and mastitis resistance. This model can be used to estimate the effect future index traits may have on EI. In the face of increased public scrutiny, this will allow the Canadian dairy industry to evaluate the environmental impact of selection for current and novel traits.

Ethics committee

None.

Software and data repository resources

None of the data or models was deposited in an official repository.

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Declaration of interest

None.

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