Feed efficiency and methane production traits have been highlighted as both economically and environmentally important due to the growing cost of feed and rising concern of the livestock industry’s environmental impact. Current genetic progress for these traits is restrained by an undefined breeding objective for these traits due to difficulty in measuring phenotypes, the various trait definitions available, and unknown responses to selection. Feed efficiency and methane production are strongly correlated; therefore, improving one has a favorable effect on the other. This relationship can be exploited to obtain both economic and environmental progress using genetic improvement. Determining the economic value of daily dry matter intake and associated methane production is key in including these novel traits in future breeding programs. In addition, the change in emission intensity (EI) per unit change in each trait undergoing genetic selection was calculated to determine the environmental impact of current and prospective index traits. Of the traits investigated, feed efficiency, milk yield, fat yield, protein yield, herd life and mastitis resistance had a considerable effect on EI. The results of this thesis suggest that the Canadian dairy system is continuing to increase sustainability and efficiency.

**Keywords:** feed efficiency, methane emission, dairy cow, selection
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I appreciate the support and guidance I have received throughout my Master’s program, however, writing an acknowledgements page was quite challenging. In the spirit of completing my journey as a Master’s student, I asked WikiHow for some assistance. An 8-step summary on “How to write an acceptance speech”.

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Finally, to summarize those that I admire, be different. Have a good attitude because you either know the answer or you don’t. Every day you are given information, but it is what you do with that information that makes you exceptional. Think for yourself and question what you don’t understand.
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CHAPTER 1: INTRODUCTION AND OBJECTIVES

1.1 INTRODUCTION

As genetic technologies continue to grow and expand, the ability to include novel traits in animal breeding programs increases. Previous constraints such as low heritability, difficulty with data collection in small populations and variation in measuring techniques made routine evaluation of novel traits difficult. However, the implementation of genomics in 2009 has highlighted new opportunities for the inclusion of novel traits into breeding programs. Some of these traits, such as metabolic disease resistance, have successfully been included in the Canadian dairy cattle genetic evaluation program, with others to follow shortly (Canadian Dairy Network; CDN, 2016a). In the near future, genomics will allow traits that improve the sustainability and efficiency of the Canadian dairy industry to be considered for inclusion in the national breeding program.

Feed utilization represents a large inefficiency to the dairy system and a major expense to the producer as close to 50% of all production costs are feed-related. This expense can be greatly reduced by selecting for improved feed efficiency. Successful selection for more feed efficient animals has been historically observed in other species for meat production (swine, poultry, beef, aquaculture) and egg production (poultry). There has previously been an interest in determining the effects of selection for feed efficiency in the dairy industry; however, the high cost of collecting phenotypes for a prolonged period delayed the inclusion of feed efficiency into the breeding program. Now, due to the introduction of new technologies such as genomics and the opportunity for international data collaboration, this trait can be further explored in dairy cattle with the intent of inclusion in future national genetic evaluations (CDN, 2016b). In addition to feed-related expenses, feed
consumption is directly related to methane output, which is another concern of the Canadian dairy industry.

Canada’s greenhouse gas (GHG) emissions are predominately carbon dioxide (79%) with methane emission (14%) and nitrous oxide (5.4%) following (National Inventory Report, 2017). The agricultural industry represents 8% of the total national GHG emission output in Canada with large emphasis being placed on its role in methane and nitrous oxide production. Enteric methane production specifically has been associated with raising and maintaining ruminant production animals. Ruminants are a division of animals, including cattle, sheep and goats, that have the ability to utilize plant-based diets through the process of foregut fermentation or rumination. The process of fermentation allows ruminants to turn human indigestible products to energy dense feeds. However, through this process some of the energy made available is lost to the production of enteric methane. Although not all methane produced by the cow is enteric methane, this process accounts for 89% of the methane produced by cattle and is a significant source of inefficiency.

Dairy cattle have been increasingly scrutinized for impacting global climate change by media and politicians. With the signing of the Paris Agreement in 2016, Canada has promised to decease its total GHG emissions by 30% of 2005 level by 2030; putting further pressure on the dairy industry to move towards sustainability and efficiency. Previously, due to the high cost of measuring phenotypes, unknown direct and indirect trait correlations and undetermined selection impact, selection for these novel efficiency traits in cattle was not optimal. However, due to genomics, future selection programs can now be successful.

In order to include these traits in the national selection indexes, further understanding of the economic impacts, selection responses, and optimal trait definitions is required. In addition, an examination of the environmental impact of the current and prospective national selection program is necessary to determine future breeding objectives. Prompt inclusion of
these novel traits in the national indexes moves towards creating a sustainable industry that benefits the producer and greater society by increasing return-on-profit, decreasing environmental footprint, fulfilling political agreements, and producing ecofriendly products.

1.2 OBJECTIVES

The specific objectives of this research were:

1) To evaluate the cost of feed throughout the life stages of the average dairy animal and determine the economic value of daily dry matter intake and associated methane production when selecting for greater feed efficiency in a first parity lactating cow for the Canadian dairy industry

2) To investigate the environmental impact of the current Canadian dairy system by calculating the industry’s emission intensity (EI) and determining the intensity value (IV) and effect of each trait included in the existing and prospective national selection indexes.

1.3 THESIS STRUCTURE

This thesis will investigate the preliminary inclusion of feed efficiency and methane emissions into the Canadian national selection index. In Chapter 2, the possible trait definitions, direct and indirect response to selection, the relation between feed efficiency and methane emissions, and the inclusion of feed efficiency in current national indexes will be reviewed. Methodology to determine the economic value of feed efficiency and associated methane production will be developed in Chapter 3. The EI of the current Canadian dairy industry and its primary trait IV will be investigated in Chapter 4. Finally, Chapter 5 will present a general discussion, including implications, future studies, and conclusions.
1.4 REFERENCES

Canadian Dairy Network. 2016a. Improving existing traits and adding exciting new ones.

Canadian Dairy Network. 2016b. Selection for increased resistance to metabolic disease.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Environmental sustainability is a growing concern for global industries. Altering current management practices and production designs to lower greenhouse gas emissions and increase efficiency has been highlighted in government policies and corporation objectives (Wall et al., 2010; Hagemann et al., 2011). Improving gross efficiency in agricultural commodity production is a major priority for industry leaders, consumers, and producers. In the global dairy market, inefficient utilization of feed and high production of emissions associated with raising and maintaining cattle are scrutinized for contributing to environmental degradation, and have therefore become targeted areas for improvement (Hagemann et al., 2011; Herrero et al., 2016). A new prospect for decreasing the environmental footprint of the dairy industry is to increase feed efficiency (FE) and decrease methane emissions (ME) through selection of genetically superior animals (Wall et al., 2010). Increasing the number of more efficient animals is not only environmentally favorable, but also of high economic interest, as feed is a large proportion of production costs (Herrero et al., 2016). Due to the multitude of phenotypic measurement techniques and the difficulty identifying the best trait for selection, uncertainty exists in determining the direct and indirect effects of selecting for animals in terms of environmental efficiency (Hagemann et al., 2011). Developing a breeding program based on such uncertainty is challenging, as the full impact of selecting for these novel traits is unknown. Therefore, it is vital to gain a full understanding of the relationships between efficiency traits and other traits currently under selection. In order to achieve this, a conclusive definition of FE and methane production traits is required.
Early hypotheses proposed selection for small mature body size as a breeding objective, as smaller cows may be more efficient in converting feed compared to their larger counterparts (Yerex et al., 1988). This was supported by the correlations found between gross FE and BW, wither height and heart girth of -0.12, -0.04, and -0.16, respectively; where gross FE is measured as energy in milk/energy in feed (Mason et al., 1957). Dickinson et al. (1969) found an even stronger correlation of -0.41 between gross FE and BW in Holsteins. This was later challenged by Veerkamp (1998), who argued that previous selection programs did not account for the limitations of gross FE to target efficiency of feed utilization directly, and therefore, selection for smaller cows, once unadjusted for BCS, would actually further increase negative energy balance instead of improving efficiency. Since then, additional traits for FE have been defined which attempt to capture the genetic variation associated with the more efficient utilization of feed by the animals.

Before developing a definition for an efficiency trait, a clear understanding of breeding objectives is required. With regard to efficiency, selection goals have been categorized into two definitions of superiority in dairy cows. The first aims to select an animal which is able to maintain current production yield while utilizing less resources, and the alternative, is an animal which is able to maintain resource utilization while exceeding current production yields. Investigating FE, this translates to differentiating between breeding programs that will result in animals that consume less feed at the same level of milk production, or generate a higher milk yield for the same feed intake. In respect to ME, selection goals are divided between animals that produce less enteric methane at the same milk yield, or have higher milk yield at the same level of enteric methane. In addition to developing a definition for each trait, the interactions between traits are investigated to determine the ultimate breeding objective. Once developed, a sub-index reflecting the
economic value of efficiency traits can be established and included in the national dairy performance index.

2.2 DEFINING FEED EFFICIENCY

Breeding programs are designed to develop highly profitable animals. This can be achieved by exploiting as few resources as possible while generating a commercial product. For the dairy industry, this translates into increasing production while limiting costs. Because feed comprises a large portion of production costs, FE has a strong impact on determining overall farm production efficiency and profitability (Veerkamp, 1998). Feed efficiency as a trait exhibits great genetic variance, making it a compelling candidate for genetic selection (Coleman et al., 2010). However, due to the complex biological processes associated with calving and lactation, it is difficult to appropriately measure and define FE traits in dairy cows (Pryce et al., 2014). Traits can typically be divided into one of three sub-categories: residual traits, ratio traits, and total intake traits. Each subclass of trait definitions has both beneficial and detrimental aspects. Moreover, re-ranking of animals may occur depending on which of the currently proposed definitions of FE is used in the breeding program (Coleman et al., 2010).

Residual feed intake (RFI) is currently the most frequently used measure of animal FE and is defined as the difference between actual and predicted dry matter intake (DMI), corrected for energy requirements including maintenance, lactation and pregnancy (Kennedy et al., 1993). Both historic and recent estimates of RFI heritability range from 0.05 to 0.38, with most estimates in lactating animals of approximately 0.20 (Van Arendonk et al., 1991; Coleman et al., 2010; Pryce et al., 2015). Selection based on RFI favor animals with the lowest RFI values, indicating that the animal is consuming less than expected based on production and other adjustment factors. Although RFI values vary throughout lactation,
measurements taken in mid-lactation have been shown to accurately represent RFI averaged over the entire lactation as BCS and BW are generally increasing in mid-lactation (Berry et al., 2003). The possibility of using measurements taken from growing heifers to predict FE in lactating animals has also been explored. A genetic correlation of 0.67 (0.45) has been estimated between the RFI of growing heifers and first lactation cows. This suggests that measurements taken on growing animals may be included in a selection program to increase the accuracy of predictions; however, the large SE of this correlation suggests that RFI in growing heifers may not be appropriate for use as a proxy trait for RFI in lactating cows (Pryce et al., 2015). A study by Coleman et al. (2010) determined that RFI may represents only 14% of the genetic variance observed for differences in DMI, giving motivation to investigate other traits which may better describe the observed variation.

An alternative residual trait which has been suggested as a working definition of FE in lactating animals is Residual Solids Production (RSP). Calculated similarly to RFI, RSP is the actual milk solids produced relative to the expected solids produced based on the feed intake of an animal and other energy sinks or energy sources (Coleman et al., 2010). Compared to RFI, this definition requires fewer trait measurements for adjustments at the phenotypic level and explains 23% of the variation in milk solids, suggesting that greater genetic gain may be achieved through selection on RSP compared with RFI (Coleman et al., 2010).

To capture the variation observed in both milk components and DMI, Residual Intake and Solids Production (RISP) is an amalgamating method of measuring FE. This trait, defined as the difference between RSP and RFI, considers both feed consumption and milk components produced. Animals with high genetic merit for RISP will eat less and have greater milk yield than their contemporaries (Berry and Pryce, 2014).
For residual traits, it is not possible to objectively differentiate low-yielding, low-
DMI-consuming animals from high-yielding, high-DIM-consuming animals who
proportionally produce the same amount of milk for the consumed DMI (Pryce et al., 2014).
In addition, all modes of energy loss or “feed sinks” must be measured, as adjustments are
made at the phenotypic level, causing this method to be computationally and labor intensive.
Residual traits also lack consistency in definitions as each model adjusts for different “feed
sinks”, further increasing data variation (Berry and Crowley, 2013).

Ratio traits have also been used to define FE. Feed Conversion Ratio (FCR) is
generally used in determining efficiency for growing animals and is defined as the ratio of
feed consumed to weight gained. This traits has low to moderate heritability (0.14 to 0.32)
and, comparable to RFI, a lower FCR has been argued to be more favorable (Gunsett, 1984).
This definition, however, may not be effective for use in lactating animals as it targets
efficiency for meat production associated with growth and may not target improving the
efficiency of producing milk and milk components (Berry and Crowley, 2013). In lactating
animals, the efficiency ratio is reflected through Feed Conversion Efficiency (FCE). This
trait is defined as kilograms milk production per unit feed intake and has a moderate
heritability of 0.33 (Nieuwhof et al., 1992; Vallimont et al., 2010; Berry and Crowley, 2013).

Ratio trait responses to selection are difficult to predict as it is unclear which
 constituents of the ratio are being altered by selection pressures, especially in cases where the
heritabilities of the involved traits are similar (Gunsett, 1984). This would be the case for
feed efficiency, defined as kg milk/ kg DMI, as milk yield and DMI are highly correlated and
have moderate heritabilities. This definition also may not take into consideration tissue
mobilization which could have negative effects on fertility and health (Roche et al., 2007).

Comparing definitions of feed efficiency that use residual or ratio traits is difficult.
For example, FCR may be a measure of production efficiency and not a direct measure of FE.
In contrast, RFI and RSP may measure FE, but not necessarily production efficiency (unit output per unit input), as these definitions do not include the partitioning of energy for each of the economically important traits. Therefore, animals that are using more energy for maintenance will not be identified (Berry et al., 2014).

Direct selection on feed intake by including EBVs for DMI in the selection index has been proposed by Veerkamp et al. (2013). As DMI values account for the feed consumed due to growth, maintenance and production, additional adjustments for differences in animal body size or milk component ratios would not be required. Measurements of DMI can be completed on a greater reference population in comparison to other definitions of feed efficiency as additional measurements on “feed sinks” may not be required (Veerkamp et al., 2013). This would be beneficial when combining data from international sources as definitions of RFI vary between international partners (Coleman et al., 2010; McParland et al., 2014; Hurley et al., 2015). However, as the relationship between DMI, production and maintenance may be non-linear, some concern regarding the computational flexibility of DMI arises and needs further investigation (Veerkamp et al., 2013).

Kennedy et al. (1993) argued that selection for both individual production traits and DMI could elicit the same selection response achieved through direct selection on RFI. There is strong genetic dependency between RFI, its component traits, and feed intake. As well, applications of RFI would likely include joint selection on RFI and its components. Therefore, a selection program which directly utilizes DMI in conjunction with RFI component traits, such as BW, BCS, maintenance and production, adjusted at the index level should be sufficient to achieve selection objectives with minimal computation and data measurements.

In addition to the difficulties associated with developing a working definition for FE and unifying data sources, the cost of collecting reliable phenotypes for analysis, as well as
the selection responses of all traits which may occur when FE is implemented within a breeding scheme, indicates another barrier.

### 2.3 FEED EFFICIENCY: POTENTIAL ANTAGONISMS

Each trait discussed previously will have varying effects on other traits currently used in the breeding program, as well as biological processes such as digestion, lactation and tissue mobilization. Based on the definition of FE and the determined breeding objective, selection response may result in different outcomes. However, an overall understanding of the possible responses in other index traits which may occur directly or indirectly due to selection for FE is essential in establishing national breeding programs.

Selection for higher FE has the potential to lower the daily DMI of the animal, as traits such as RFI favor lower consuming cows (Veerkamp et al., 2013). The primary concern when selecting animals that exhibit lower feed consumption is the effect it may have on appetite and dominance behaviors, drivers of negative energy balance. Animals that exhibit lower appetite are more likely to have increased occurrence of ketosis, fatty liver, and unfavorable changes in protozoa (Steen, 2001). In addition, these animals may also be predisposed to abomasum displacement post-calving. Burfeind et al. (2011) determined that changes in rumen fill are highly correlated with changes in DMI. As feed intake is generally lower post-calving, accentuated low appetite during this time period caused by selection could potentially increase the prevalence of abomasal displacements.

In contrast, animals who have been selected for high levels of milk production per kilogram of feed could also exhibit a high prevalence of metabolic disorders and decreased fertility. Strong evidence has been presented which shows that animals with higher genetic merit for milk production at first calving have lower BCS throughout lactation (Veerkamp, 1998). This effect could be a consequence of the animals heightened ability to mobilize body
tissue. This aspect may appear to increase the animal’s efficiency, however, the process of depositing and then mobilizing fat is biologically inefficient and concerns arise when investigating the effects increased tissue mobilization has on fertility. A cow must have sufficient body tissue reserves in order to conceive and maintain a pregnancy to full term. When energy reserves are insufficient in early lactation, both fertility and health are impacted negatively (Veerkamp, 1998). Wathes et al. (2007) noted that excessive tissue mobilization caused by negative energy balance can impair health and fertility in high-yielding cows. Collard et al. (2000) also reported detrimental effects on digestion (milk fever, displaced abomasum, ketosis) and locomotion with extended periods of negative energy balance. This was confirmed by Bastin et al. (2010) who found negative correlations between BCS and calving to first service, first service to conception, and days open, and a positive correlation between BCS and 56-d non-return rate at first insemination. Increased tissue mobilization has been associated with prolonged calving interval and, more specifically, the delay of normal ovarian activity (VandeHaar and St-Pierre, 2006; Bastin et al., 2010). Therefore, as the genetic relationships between BCS and fertility traits are favorable, BCS could be used in selection programs in combination with FE to increase reproductive performance (Bastin et al., 2010).

Previous research suggests that RFI is likely correlated with BW and production, as these are corrected for in the model. However, often changes in BCS are not accounted for very accurately in the adjustment, and this therefore results in an unfavorable association between RFI and BCS. Fat is a very energy-dense tissue, and cows that are either depositing less, or mobilizing more, appear to have much lower feed requirements than others. This response is seen in selection for FE using RFI in pigs, where selection for FE is strongly associated with increased leanness (Young et al., 2011). In dairy cattle, RFI has been unfavorably associated with daughter fertility rate, cow conception and heifer conception rate
Pryce et al. (2015) confirmed this relationship and found a low unfavorable genetic correlation of 0.10 between fertility and RFI. This again indicates that cows genetically selected to have lower RFI may have poorer fertility.

In addition, RFI has a negligible correlation of almost zero with concentrate consumption. It is therefore likely that increased FE, based on RFI, will decrease roughage consumption, which may have negative effects on rumen health and digestion (Van Arendonk et al., 1991). Van Arendonk et al. (1991) described the economic value of FE as the result of replacing energy from concentrates by energy from roughages and reducing undesirable effects of negative energy balance on health and reproduction.

In contrast to previous work, Manafiazar et al. (2016) found a favorable significant relationship between average BCS and RFI. This supports the conflicting theory that efficient animals should be able to maintain an increased BCS. Should this be possible, concern regarding the effects of efficiency on health and reproduction directly related to insufficient body tissue stores would be minimized. Van Arendonk et al. (1991) explained that RFI has zero phenotypic correlation with production traits and BW; therefore, selection for improved FE using RFI is not likely to result in negative correlated responses in these traits. However, this is in contrast to work done by Veerkamp et al. (1995) that reported unfavorable moderate genetic correlations between RFI in lactating animals and subjectively scored BCS. In principle, if fertility and metabolic disorders are included correctly in the breeding objective, selection for RFI should still be able to progress proficiently, even in the presence of unfavorable correlations, as long as these unfavorably correlated traits are evaluated accurately and in a timely way.

Vallimont et al. (2011) reported a genetic correlation of 0.87 between FCE and milk yield with an unfavorable genetic correlation of -0.70 between FCE and BCS. In addition, Coleman et al. (2010) reported similar results, as a favorable FCE had a positive association
with increased milk yield and solids production with a lower consumption of feed and a reduction in BCS. This preludes to the concept that selection for more feed efficient animals may cause poorer health and reproduction due to insufficient energy reserves, if not monitored consciously.

There is still large uncertainty on how selection for FE will affect the health and reproductive abilities of dairy cattle. Studies have indirectly linked FE to decreased fertility and an increased prevalence of metabolic disorders, however further investigation into the exact repercussions when selecting solely for FE are required.

2.4 DEFINING A METHANE EMISSION TRAIT

Enteric methane is a greenhouse gas (GHG) of interest to the dairy industry, as 89% of livestock-derived ME originate from enteric fermentation (Jiao et al., 2014). Pressure is placed on the dairy industry to lower its GHG emission, and, in particular, the emissions from animal production. The development of new technology with the ability to trap and convert gasses to be repurposed for energy has previously been investigated (Patra and Patra, 2012). The genetic variation for ME that exists between animals offers an alternative strategy for emission minimization that would be both cumulative and permanent. However, the various measurement techniques used for quantifying methane output, reviewed by Brouček (2014), highlight additional challenges in determining the most appropriate methane trait for use in animal breeding.

Methane emission has low to moderate heritability, depending on measurement technique and trait definition. Lassen and Løvendahl (2016) determined heritability estimates of 0.21 for daily methane production and methane per liter of milk produced. In addition, a similar heritability of 0.16 was recorded for predicted ME based on the ratio of CO₂:CH₄ (Lassen and Lovendahl, 2016). Methane production, measured in grams or grams/day, is
strongly associated with the amount of feed eaten by an animal in a day (Johnson and Johnson, 1995). Thus, improvements in FE can lead to reduced ME depending on trait definitions. In contrast, methane yield (g methane/ kg DMI) is independent from the decrease in methane caused by reducing total feed intake and describes the additional improvement in methane output from a direct methane trait.

Alternatively, the intensity of emission production of a breeding system may be included in selection programs. Emission intensity (EI) is defined as the ratio of all GHG emissions produced compared to the product output of the system (Herd et al., 2004; Amer et al., 2017). The methodology used to determine EI also allows direct evaluation of the effect of individual traits on the system to be measured (Amer et al., 2017). Emission intensity accounts for improvements in system efficiency by highlighting index traits, which have a favorable trend of efficiency to lower emissions per unit output. Residual methane has also been proposed as a potential trait definition and is based on the same concept as RFI. This concept uses a regression model to determine residual methane production based on DMI and production traits; however, it has not been widely utilized (Berry and Crowley, 2013). Further research on the challenges and benefits of possible trait definitions and associated trait correlations is required to determine superiority between the suggested phenotypes.

### 2.5 METHANE EMISSIONS: POTENTIAL CONCERNS

Continual selection for milk yield has resulted in animals that eat more feed and therefore have higher output of ME. Variability of ME in terms of methane per unit feed is unknown and interpretations require caution, as reported variability may actually be due to the genetic variation of FE (Berry et al., 2013). Similarly, estimates of heritability for direct methane yield may also be artifacts of selection for FE. However, Lassen and Lovendhal (2015) suggested that predicted gross methane (g or g/day) adjusted for the correlation
structure with milk yield may be the most correct way to include methane in a breeding program. In a study by de Haas et al. (2012), animals with low genetic merit for predicted ME (g/d) produced approximately 60kg more enteric methane/lactation compared to animals with the same level of fat-and-protein corrected milk production. Predicted ME showed large variation between cows, once again in part due to FE.

Historical increases in volume of emissions per animal are masked by the increase in production efficiency, as fewer animals are required to produce the same volume of milk, therefore doubling efficiency through the dilution of maintenance (Pryce et al., 2014). Selection for traits which increase production, longevity and reproduction improve the EI of the system and therefore, less methane is produced per kg of milk product output (Lovett et al., 2006; Beukes et al., 2010; Herrero et al., 2016). Amer et al (2017) proposed a methodological approach to determine EI of livestock production systems, as well the intensity values of traits in current Irish dairy selection indexes. Results, which identified survival, production and calving interval as key influential traits, were consistent with previous investigations (Lovett et al., 2006; Beukes et al., 2010; Herrero et al., 2016). As EI is a multi-faceted trait, further investigation is required to determine its role in future national breeding programs.

The genetically unfavorable correlation between milk yield, feed consumption and methane production poses a challenge for decreasing total emissions (Lassen and Lovendahl, 2016). This challenge may be overcome by using indirect selection of other traits which focus on lowering feed consumption. Egger-Danner et al. (2012) suggested that lowering RFI reduces ME per day, paving the way for future research to be conducted to determine the relationship between ME and all working definitions of FE.

Direct selection for reduced methane proves challenging, as measurement techniques are difficult and expensive (Pryce et al., 2014). However, associated traits such as RFI may
be used to generate genetic improvements (de Haas et al., 2012). The standard methodology used to estimate methane production is a three-tier system published by the Intergovernmental Panel on Climate Change (IPCC). Organization of tiers is based on the country’s database quality, with tier 1 requiring the simplest calculation and tier 3 utilizing the most complex and computationally demanding techniques. This system is based on the methane produced from the cow’s gross intake of feed. Methane estimates are expressed in kg/cow/day. As calculations become more sophisticated, greater data on the digestibility and nutrient component of rations is required (Strom et al., 2012).

Methane emissions per day vary greatly throughout lactation, as shown by a correlation of only 0.36 between the beginning and end of lactation (de Haas et al., 2012). Predicted ME and RFI have a correlation of 0.51 to 0.66, depending on stage of lactation (de Haas et al., 2012), suggesting that FE and ME traits are interconnected. Furthermore, a genetic correlation of 0.44 exists between RFI and true methane output, confirming that cows with higher genetic merit for FE have lower true enteric methane production (de Haas et al., 2012).

Very few reports investigate the interactions present between ME and other traits. Genetic correlation between ME and cow live weight is low, suggesting that health and reproductive traits associated with BCS should not be strongly affected by selection (Lassen and Lovendahl, 2016).

2.6 INVESTIGATING THE FUTURE OF FE AND ME IN GENETIC EVALUATIONS

Studies have suggested investigating FE and ME as cohesive traits. These novel traits have a high correlation and are tightly linked through biological processes. Completing genetic evaluations with FE and ME in combination may increase the accuracy of
estimations. To ensure that appropriate weighting design of selection index is achieved, collection of a sizable dataset to ensure proper estimation of genetic relationships between FE, ME and other traits is required. The cost associated with phenotypic data collection for these two novel traits is currently large, leading to a small sample size collected in practice which may result in erroneous evaluations. Li et al. (2016) attempted to increase the sample size of their study on DMI by combining breeds together in genetic evaluation to overcome the large standard errors. Genetic correlations of DMI between breeds was high and significant between 5 and 24 weeks of lactation, however breed variance components could be different and need to be accounted for in evaluations individually. Manzanilla-Pech et al. (2016) successfully validated Angus beef RFI genomic predictions in Holsteins, offering new possibilities for combining datasets to increase accuracies of genetic EBVs. An alternative option for overcoming the barriers associated with small sample size is the consolidation of databases from international partners (Veerkamp et al., 2013). The increase in volume of phenotypic data achieved by including data resources from multiple partners will allow for more accurate genetic evaluations with smaller standard error.

2.7 INCLUSION IN NATIONAL BREEDING PROGRAMS

International research initiatives are currently underway to implement FE and ME in national breeding programs. A collaborative initiative which brings together Canada, Australia, Denmark, United States, Switzerland and the United Kingdom aims to deliver a worldwide database for FE and ME. Data exchange between partners is expected to greatly increase the population size and improve genomic evaluations for these novel traits. In addition, other European countries are also interested in participation to develop EBVs for these efficiency traits (ICAR).
Feed efficiency is currently incorporated in the Australian breeding program through the recently developed “Feed Saved” trait (Pryce et al., 2015). A value for the animal’s lifetime RFI is predicted by combining the RFI of Australian calves and Australian lactating cows. Feed Saved uses the lifetime RFI in combination with mature BW to produce an efficiency value, which segregates animals of the same RFI into different groups based on energy requirements:

\[
\text{Feed Saved} = \frac{\text{Feed}}{\text{BW/kg}} - \text{RFI}_{\text{life}}
\]

The Feed Saved trait results in saving approximately 1% of annual feed costs for animals 1 standard deviation above the mean (Pryce et al., 2015). Therefore, a selection program which includes Feed Saved would further increase economic gain.

Feed Saved has great versatility in manipulating the efficiency of animal based on breeding objectives. The variation of Feed Saved improves gross efficiency as more product is produced per unit of maintenance (Pryce et al., 2015). Previously, in the Australian Profit Ranking Index (APR), Feed Saved was used to breed for animals that trend towards feed inefficiency, but at a slower rate than in previous selection programs. Gonzalez-Recio et al. (2014) simulated the incorporation of RFI into the APR, resulting in an expected reduction in RFI of 1.76 kg/cow per year. The proposed index would produce heifers with reduced feed intake and had only a small impact on production. In contrast, inclusion in the current national selection index, the Australian Balanced Performance Index (BPI), is expected to create a genetic improvement in FE of 0.5 kg/year; which translates to $0.15 profit/cow/year of selection. Using BPI, animals with an EBV 1 SD above the mean (+66kg/yr) will save approximately 1% of total yearly feed. Depending on the specified breeding objective, this selection method may affect appetite and dominance behavior. Further research is needed on how selection for BPI will affect other traits and possible adjustments which can be made to prevent negative effects to health, reproduction and behavior (Pryce et al., 2015).
Additional feed efficiency traits are being investigated for incorporation in other national indexes. The USDA (2017) is currently exploring a similar efficiency trait which combines adjusted RFI with the feed required for increased body weight. Current studies suggest that the large economic value for a trait similar to the Australian feed saved could result in an emphasis of 20% in the US Total Net Merit index; however, this genetic progress is limited by low reliabilities (USDA, 2017). The increase in feed intake records proposed by global collaborations is expected to address this constraint.

Additionally, Canada is building a database of daily DMI records to calculate genomic EBVs for FE. These EBVs are based on DMI corrected at the index level for energy sinks related to production, growth, maintenance, and reproduction and are projected to be available and incorporated into the nation selection index by 2020 (CDN, Guelph, 2015). In the Netherlands, a direct DMI index, which combines the consumed daily DMI and EBVs for indicator traits by lactation, was used to determine a genomic EBV for DMI (Veerkamp, 2014). The current integration of FE into international breeding programs encourages the inclusion of other novel traits, such as ME, into future breeding programs.

2.8 CONCLUSIONS

Inclusion of FE and ME into national breeding programs requires careful consideration of the various trait definitions, possible interactions and optimal breeding objectives. Based on the efficiency trait definitions explored, DMI adjusted at the index level for growth, reproduction and maintenance may be most favorable as a FE trait definition in non-pastoral based dairy systems. In addition, an ME trait expressed as kg methane/ kg DMI should be explored for inclusion in the national index. Further research is required to determine the role of emissions intensity as either an index trait or as an evaluation method for determining the environmental effect of current and future selection programs.
2.9 REFERENCES


Hot topic: Effect of breeding strategies using genomic information on fitness and health.
Gunsett The online version of this article , along with updated information and services ,
Lovett, D.K., L. Shallow, P. Dillon, and F.P. O’Mara. 2006. A systems approach to quantify


CHAPTER 3: ECONOMIC VALUE OF EFFICIENCY TRAITS

3.1 ABSTRACT

Feed represents a substantial proportion of all production costs in the dairy industry and is a useful target for improving overall system efficiency and sustainability. The objective of this study was to develop methodology to estimate the economic value for feed efficiency and associated methane production. The model can be used to calculate the level of economic savings achieved by selecting animals that convert consumed feed into product while minimizing the feed energy used for inefficient metabolism, maintenance, and digestion. In the economic model developed, the trait Feed Performance, measured as a 1 kg increase in more efficiently used feed in a first parity lactating cow, is used to derive the total lifetime value of more efficiently used feed via correlated selection responses in other life stages. The resulting improved conversion of feed was also applied to determine the cost savings associated with the lower output of emissions, where methane yield is defined as kg methane/kg DMI. Overall, increasing the Feed Performance EBV by one unit (i.e. 1 kg of more efficiently converted DMI during the cow’s first lactation) translates to a total lifetime saving of 3.25 kg in DMI and 0.055 kg in methane with the economic values of CAD $0.83 and CAD $0.07, respectively. Therefore, the estimated total economic value for Feed Performance is CAD $0.90/unit. The proposed model is robust and can be applied to determine the economic value for feed efficiency traits in other production systems and countries.

3.2 INTRODUCTION

The stable revenue provided by the national dairy industry has a vital impact on maintaining a thriving economy in Canada. In 2015, the Canadian dairy industry generated CAD $23.7 billion in revenue and maintained or created nearly 221,000 full-time equivalent
jobs directly and indirectly related to on-farm production, including processing plants or other production and processing sectors. This represents a 3% increase in revenue and 5% increase in employment since 2013 (Dairy Farmers of Canada, 2015). The increasing consumer demand for an inexpensive product along with the added pressure from international competitors has forced producers to be as efficient as possible to maximize profit. In order to continue thriving as an industry, producers must maximize production efficiency, as the cost of feed, housing, and other expenses are continually increasing. The rising cost of feed has placed great pressure on producers to maintain an economically sustainable production system. A high proportion of Canadian dairy production costs are attributed to feed-related expenses. Breeding programs have been effective in improving production efficiency through increasing milk yield and milk solids, and more recently, by improving health and reproduction (Miglior et al., 2005; Van Doormaal and Beavers, 2016).

Although feed efficiency may be improved through nutrition and management, the variation observed in dry matter intake (DMI) between animals makes feed efficiency an excellent candidate for improvement through genetic selection programs. Genetic selection offers cumulative and permanent long-term improvement of the animals themselves; therefore, the advantages achieved are greater and more cost effective than results obtained through changes in nutrition and management practices alone. Additionally, selection for increased feed efficiency results in indirect genetic gain for lower methane production (Waghorn and Hegarty, 2011).

The definition of feed efficiency explored here addresses the problem of unfavorable correlated responses in selection for reduced DMI by focusing on improving the ability of the animal to convert feed into more product. This will be achieved through targeting feed usage inefficiencies, whereas alternative definitions may target feed reductions per unit product. The definition used in the current study is more likely to be adopted by the Canadian dairy
producer as it takes into consideration that a decrease in DMI is likely undesired, as producers seek animals with appetite that can transform the DMI into milk production, and energy for maintenance and growth as efficiently as possible.

Environmental sustainability is a growing concern for global industries. In 2015, Canada produced greenhouse gas (GHG) emissions totaling 723 Mt of carbon dioxide equivalents. Of this, 10% was attributed to the agriculture sector and 62% of that to livestock (Environment Canada, 2016). With newly announced government policies for decreasing the GHG produced in Canada by 30% of 2005 levels by 2030, strong pressure has been placed on the dairy industry to lower its environmental footprint by targeting a reduction in enteric methane production, and to continue to become a more sustainable industry. The objective of this study is to estimate the economic value of daily DMI and associated methane emissions by developing a methodology that can be used to determine the marginal economic value of a unit change in a feed efficiency selection criterion which simultaneously incorporates an associated reduction in methane production.

3.3 MATERIALS AND METHODS

3.3.1 Trait Definitions

This study assumes a feed efficiency selection criterion trait will become available for selection of Canadian dairy cattle. This criterion reduces the amount of feed wasted on inefficient digestion, excess animal maintenance of live weight, and metabolic inefficiency initially in a first lactation cow. We define this trait as Feed Performance (FP); its expected units are in kg of more efficiently used feed to avoid problems associated with selecting on ratio traits (Gunsett, 1984). The rationale for this trait definition is considered in detail in the discussion.
In order to determine the cost of feed per animal unit, the lifespan of a typical Canadian dairy animal was segmented into stages. Life stages were established based on significant changes in cost of ration or energy requirements by the animal (Table 3.1). Data were provided by Valacta (Sainte-Anne-de-Bellevue, QC), and represent costs from herds in Quebec, Canada, which encompasses 49% of all Canadian dairy herds. The replacement heifer stage was further segmented based on weight and growth to determine the total cost of feed consumed from weaning (49 d; Zwald et al., 2007) until age at first calving (25.8 mo). Average days spent in each life stage (lactating and dry) were calculated using national data provided by the Canadian Dairy Network (CDN; Guelph, ON). The average age at first calving, days dry, and calving interval was provided by the CDN national data base for the Canadian Holstein population in 2016.

Table 3.1: Life stage specific constants used in model to calculate the economic value of feed performance due to direct selection and the correlated responses for each life stage

<table>
<thead>
<tr>
<th>Life stage</th>
<th>Days in life stage</th>
<th>Total kg DMI</th>
<th>CAD $/kg DMI</th>
<th>( r_{g\text{DMI}} )</th>
<th>( r_{g\text{Methane}} )</th>
<th>Discount factor</th>
<th>Survival factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-weaned</td>
<td>49</td>
<td>29.40</td>
<td>4.43</td>
<td>0.67</td>
<td>0.67</td>
<td>1.147</td>
<td>1.00</td>
</tr>
<tr>
<td>Growing heifer</td>
<td>717</td>
<td>5932.17</td>
<td>0.22</td>
<td>0.67</td>
<td>0.67</td>
<td>1.078</td>
<td>1.00</td>
</tr>
<tr>
<td>1(^{st}) lactation milking</td>
<td>355</td>
<td>6863.45</td>
<td>0.29</td>
<td>1.00</td>
<td>1.00</td>
<td>0.968</td>
<td>1.00</td>
</tr>
<tr>
<td>1(^{st}) lactation dry</td>
<td>65</td>
<td>799.50</td>
<td>0.25</td>
<td>1.00</td>
<td>1.00</td>
<td>0.931</td>
<td>0.75</td>
</tr>
<tr>
<td>2(^{nd}) lactation milking</td>
<td>355</td>
<td>8234.62</td>
<td>0.29</td>
<td>0.88</td>
<td>1.00</td>
<td>0.895</td>
<td>0.75</td>
</tr>
<tr>
<td>2(^{nd}) lactation dry</td>
<td>67</td>
<td>824.10</td>
<td>0.25</td>
<td>1.00</td>
<td>1.00</td>
<td>0.861</td>
<td>0.65</td>
</tr>
<tr>
<td>3(^{rd+}) lactation milking</td>
<td>360</td>
<td>8595.54</td>
<td>0.29</td>
<td>0.80</td>
<td>1.00</td>
<td>0.782</td>
<td>0.65</td>
</tr>
<tr>
<td>3(^{rd+}) lactation dry</td>
<td>71</td>
<td>873.30</td>
<td>0.25</td>
<td>1.00</td>
<td>1.00</td>
<td>0.800</td>
<td>0.50</td>
</tr>
</tbody>
</table>

\( r_{g\text{DMI}} \) is the genetic correlation for DMI between first parity lactating cows and all other life stages and \( r_{g\text{Methane}} \) is the genetic correlation for methane/kg DMI between first parity lactating cows and all other life stages (Gonzalez-Recio et al., 2014; CRV, 2016)

\(^{1}\)Based on data provided by CDN (2016) and Zwald et al (2007)

\(^{2}\)Based on data provided by Valacta, Quebec
3.3.2 Calculating the Price of Feed (CAD $/cow/day)

The average cost of feed per life stage is provided in Table 3.1. Calf estimates were based on a milk replacer diet and did not include the use of waste milk (Zwald et al., 2007). The total cost of feed during heifer rearing was calculated based on previous work by Zwald et al. (2007), which determined feed consumption relative to age and weight. An inflation rate of 1.53% and an exchange rate of 0.93 USD were applied to obtain a present value in Canadian dollars, based on historical economic data from the Bank of Canada. Costs of feed for both mature lactating and dry cows were obtained using averages from Valacta (2015) data and were determined to be CAD $5.83 and CAD $2.97 per day, respectively. Future projections for trends in feed costs were estimated and extrapolated using historical Ontario Dairy Farm Accounting Project Reports from 2005 to 2015 (Canadian Dairy Commission, 2016). Future costs to producers for Canadian feed prices were projected to increase by CAD $95.06/cow per year (Figure 1). The NRC (2001) computer feed budgeting and optimization program was used to determine values for energy requirements and average dry matter intake for all life stages, excluding the growing heifer stage, which was determined using model estimates from Zwald et al. (2007) that allowed for better economic estimates for constant growth and varying feed prices. Calves were assumed to be fed milk replacer up to an average calf weight of 90 kg. Lactating and dry cows were assumed to be 650 kg live weight. Rations used in the NRC program were representative of a typical Canadian dairy system and were provided by the Livestock Research Innovation Centre (Guelph, ON). A survival factor equivalent to the number of animals in each life stage relative to the number of cows in first lactation was applied to total feed calculations. In addition, a discount factor of 7% was applied to DMI to account for the time spent to reach later life stages (Amer et al., 2017)
Figure 3.1: Future projection for cost of feed based on historical value of dairy expenses attributed directly to feed. Future projection provided was based on historical Ontario Dairy Farmers Annual Report. Feed expense trends suggest a yearly increase of CAD$95.06/cow/year

3.3.3 Economic Weighting on Feed Efficiency

An exact selection criterion for feed efficiency in Canadian dairy cattle has not yet been established. We therefore considered a criterion trait that predicts the amount of feed wasted on inefficient metabolism, digestibility, and maintenance. This criterion is termed \( FP \) and has an economic value \( (EV_{FP}) \) reflecting the value of the feed better converted to product by having a more efficient animal. A selection trait targeting a first parity lactating cow will have a direct effect on improving \( FP \) for the first lactation, but will also have an indirect effect on the efficiency of the animal throughout all other life stages, assuming relevant genetic correlations. The \( EV_{FP} \) represents the cumulative effect of selecting for a trait in a first parity lactating cow and its correlated response with other life stages for DMI and associated methane emission. The aggregate economic value was derived as follows:
\[ \text{EV}_{FP} = \text{EV}_{FP,1} + \sum_{LS=2}^{8} \text{EV}_{FP,LS} + \text{EV}_{\text{Methane}} \]

where \( \text{EV}_{FP,1} \) is the economic value for the spared feed throughout the lactation of a first parity cow, \( \sum_{LS=2}^{8} \text{EV}_{FP,LS} \) is the cumulative economic value for more efficiently converted feed due to correlated responses in all other life stages, \( LS \), (rearing and subsequent lactations), \( \text{EV}_{\text{Methane}} \) is the economic value for the saved methane production associated with the improvement in feed conversion. The \( \text{EV}_{FP} \) for first parity lactating cows (\( \text{EV}_{FP,1} \)) and for other life stages (\( \text{EV}_{FP,LS} \)) are calculated as,

\[ \text{EV}_{FP,1} = P_{LS=1}^p \times DF_{LS=1} \]

and

\[ \text{EV}_{FP,LS} = b_{LS} \times B_{LS,1} \times P_{LS}^p \times DF_{LS} \]

respectively, where \( b_{LS} \) is the number of animals in the herd in life stage \( LS \) per first parity lactating heifer, \( B_{LS,1} \) is the approximated genetic regression of DMI in life stage \( LS \) on the DMI in a first parity lactating cow, and \( P_{LS}^p \) is the price per unit DMI of feed fed to an animal in life stage \( LS \). A discount factor, \( DF_{LS} \), is calculated as:

\[ DF_{LS} = \left( \frac{1}{1 + r} \right)^{t_i} \]

where \( r \) is the discount rate, set to 7%, and \( t_i \) is the average time difference (expressed in fractions of years) between the midpoint of the life stage and the beginning of 1st parity. Parity 3, 4, 5 are represented within the \( 3^{rd} + \) life stage. For \( i = \text{parity} 3, 4, 5 \):

\[ t_{3+} = \sum_{i=3}^{5} \left( t_i \times \frac{p_i}{\sum_{i=3}^{5} p_i} \right) \]

where \( p_i \) is the proportion of the herd in parity \( i \), and \( t_i \) is as described previously. Proportions of cows in the milking herd by life stage are shown in Table 3.2.

Regression coefficients to predict changes in feed more efficiently used in other life stages due to an improvement in feed conversion performance in first lactation were defined
assuming equal trait heritability and coefficients of variation, and that parameters for FP can be approximated by parameters for total DMI, as follows:

\[ B_{LS.1} = \frac{\mu_i}{\mu_0} \times r_{gi} \]

where \( \mu_0 \) is the total mean feed improvement in the lactation of a first parity cow, \( \mu_i \) is the mean feed improvement of a cow in \( i \) life stage, and \( r_{gi} \) is the genetic correlation for total DMI in each life stage \( i \) with total DMI of a first parity lactating cow. A summary of current DMI parameters is shown in Table 3.1. Parameters for DMI are required in order to calculate regression coefficients as ratios of feed intake across life stages. In the present study, we assumed that improved conversion of feed is an equal proportion of DMI across all life stages, however, this will need to be reviewed going forward when further information becomes available from experimental data.

**Table 3.2:** Constants used in calculation for all life stages

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming Potential of methane(^1)</td>
<td>25</td>
<td>kg CO(_2)/kg methane</td>
</tr>
<tr>
<td>Discount rate</td>
<td>7</td>
<td>%</td>
</tr>
<tr>
<td>Price of Carbon(^1)</td>
<td>50</td>
<td>CAD $/tonne</td>
</tr>
<tr>
<td>Proportion of milking herd(^3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1(^{st}) lactation</td>
<td>0.36</td>
<td>-</td>
</tr>
<tr>
<td>2(^{nd}) lactation</td>
<td>0.27</td>
<td>-</td>
</tr>
<tr>
<td>3(^{rd}) lactation(^2)</td>
<td>0.36</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^{1}\)Provided through Environment Canada  
\(^{2}\)3\(^{rd}\) lactation and dry life stages include values obtain using animals in lactation 3, 4, and 5  
\(^{3}\)Based on data provide by CDN (2016)

**3.3.4 Cost of Methane Associated with Feed Intake**

The economic value for methane (\( EV_{\text{Methane}} \)) is the value of the cumulative savings of methane associated with the feed more efficiently used over the animal’s lifetime due to a correlated response of selection for DMI of a 1\(^{st}\) parity lactating cow. The total cost of methane associated with DMI was calculated as follows:
where $b_{LS,1}$ is expressed as a ratio of the number of animals in the herd at this life stage over the number of first parity lactating heifers, $B_{LS,1}$ is the approximated genetic regression of DMI in life stage on the DMI in a first parity lactating cow, $GWP$ is the global warming potential conversion factor of methane to CO$_2$ equivalents, $DF_{LS}$ is a discount factor, $MP$ is the methane production per unit of feed, constant across all life stage, and $P_{LS}^M$ is the average price of carbon per unit based on government policy. The Canadian government has proposed a carbon tax of CAD $50/tonne which will be implemented by 2022 (Environment Canada, 2017).

### 3.3.5 Sensitivity Analysis

A sensitivity analysis was conducted on the cost of feed at the 5%, 10%, 15%, and 40% level above and below current estimated values to determine the robustness of the model. As results for methane are directly proportional to results for DMI, the sensitivity analysis was only completed on feed cost values.

### 3.4 RESULTS

### 3.4.1 Developing Economic Values

The FP trait regression coefficients show how a one unit change in feed conversion performance for a first lactation cow is expected to affect the total feed utilized by the animal throughout all life stages. The coefficients we derived imply selection responses of 0.80 kg and 0.65 kg for more efficiently used feed during the lactating periods of second and third parity cows, respectively, per 1 kg improvement in feed conversion in first lactation. Further savings of 0.58 kg of more efficiently used feed in post-weaned heifer rearing per 1 kg
improvement in feed conversion in first lactation were derived. In contrast, much lower indirect selection responses were derived for pre-weaned heifers and first, second, and third parity dry periods, with a cumulative selection response of 0.23 kg DMI for the four life stages (Table 3.3).

Overall, increasing the average genetic potential of feed efficiency of a first parity lactating cow by improving feed conversion in this life stage by 1 kg translates to a total lifetime dry matter saving of 3.25 kg. This is equivalent to a total savings of CAD $0.83 per cow per lifetime (CAD $0.28 for first parity lactating animal and CAD $0.62 for the remaining life stages). The value of methane associated with a one unit increase in FP was CAD $0.07 per cow per lifetime, equivalent to 55 g of methane. The Canadian national cost of carbon used in this study is comparable to the social cost of carbon at CAD $42/tonne most recently reported by the United States Board of Environmental Change and Society (2017). Cumulatively, the total savings associated with improving FP was CAD $0.90 per cow per 1 kg increase in feed conversion performance in a first parity lactating cow.

Table 3.3: Calculated response totals and economic values by life stage for selection per EBV of feed performance as well as the associated methane reduction

<table>
<thead>
<tr>
<th>Life stage</th>
<th>Economic value of feed gained due to selection response in each life stage, CAD$</th>
<th>Expected total lifetime of feed change per EBV, kg</th>
<th>Economic value of methane associated with feed response, CAD$²</th>
<th>Expected total lifetime methane change per EBV, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-weaned</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.05</td>
</tr>
<tr>
<td>Replacement heifers</td>
<td>0.13</td>
<td>0.58</td>
<td>0.01</td>
<td>9.84</td>
</tr>
<tr>
<td>1st lactation milking</td>
<td>0.28</td>
<td>1.00</td>
<td>0.02</td>
<td>17.00</td>
</tr>
<tr>
<td>1st lactation dry</td>
<td>0.02</td>
<td>0.09</td>
<td>0.00</td>
<td>1.49</td>
</tr>
<tr>
<td>2nd lactation milking</td>
<td>0.20</td>
<td>0.80</td>
<td>0.02</td>
<td>13.52</td>
</tr>
<tr>
<td>2nd lactation dry</td>
<td>0.02</td>
<td>0.08</td>
<td>0.00</td>
<td>1.32</td>
</tr>
<tr>
<td>3rd+ lactation milking</td>
<td>0.15</td>
<td>0.65</td>
<td>0.01</td>
<td>11.01</td>
</tr>
<tr>
<td>3rd+ lactation dry</td>
<td>0.01</td>
<td>0.06</td>
<td>0.00</td>
<td>1.09</td>
</tr>
</tbody>
</table>

¹3rd+ lactation and dry life stages include values obtain using animals in lactation 3, 4, and 5
²Additional minimal methane response, which totals to 0.01, is obtained in life stages which appear to be zero
3.4.2 Sensitivity Analysis

The results of the sensitivity analysis are presented in Table 3.4. This analysis shows the trends in economic values that would occur if the feed costs vary by ±5%, 10%, 15%, and 40%. These represent the underestimated and overestimated case variation scenarios for estimating the cost of feed. Results show the change in economic value is proportional to the change in feed costs. Neither scenario shows large detrimental changes in economic value until estimates vary by greater than 15%.

Table 3.4: Sensitivity analysis for the effect of feed costs (CAD$) on the economic value of the Feed Performance trait

<table>
<thead>
<tr>
<th></th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underestimated</td>
<td>0.87</td>
<td>0.91</td>
<td>0.95</td>
<td>1.16</td>
</tr>
<tr>
<td>Overestimated</td>
<td>0.79</td>
<td>0.75</td>
<td>0.71</td>
<td>0.51</td>
</tr>
</tbody>
</table>

3.5 DISCUSSION

3.5.1 Trait Selection for Feed Efficiency

The selection goal examined in this study is to target inefficiencies in digestion, metabolism, and maintenance, while balancing the body condition score and tissue mobilization so as to not affect the production, health, or fertility of the animal. It is widely considered by producers that selection for animals that exhibit lower feed consumption would be undesirable. This is due to the negative effect lower feed consumption may have on milk production, along with appetite and dominance behaviors as this may select animals with low motivation to compete for feed within the herd. Animals that exhibit lower appetite are more likely to have increased occurrences of ketosis, fatty liver, and unfavorable changes in protozoa (Steen, 2001; Goldhawk et al., 2009). In addition, animals with lower appetite are also predisposed to abomasum displacement and other metabolic disorders post-calving (Goldhawk et al., 2009). Feed intake is naturally lower before calving and accentuated low
appetite and submissive behaviors during this time period or directly after as a result of selection could potentially increase the risk factors for displacements and other metabolic disorders. Burfeind et al. (2011) explained that this may further decrease rumen fill as animals may not be competitive for feed. Macdonald et al. (2014) compared high and low efficiency animals and reported no unfavorable effects of selection for FE on production. However, the effects of selection for FE on animal behavior are still unknown and require further investigation.

In the current study, it is anticipated that total FP will be corrected at the index level for energy requirements associated with other EBVs linked to feed sinks. For example, the energy required for maintenance, production, health, and fertility, as well as body condition score, are all feed sinks linked to existing EBVs considered in breeding programs. This definition was used as it is computationally modest, being applied to the EBV itself rather than in the definition of the phenotypes used to compute them. It also does not require all variables or feed sinks to be measured accurately on the animals for which DMI is being recorded. In contrast, residual feed intake (RFI), currently the most frequent measure of animal feed efficiency, requires that all feed sinks be measured because adjustments are made at the phenotypic level (Kennedy et al., 1993). Collecting data and maintaining animals for DMI recording is expensive, and many of the other feed sink traits are hard to quantify on the relatively small numbers of animals in DMI studies. International collaboration and data sharing is commonly required to generate sufficient numbers for genetic and genomic prediction of DMI genetic merit. Thus, there may be inconsistencies in the methods and extent of recording of feed sinks across the different research sites.

Kennedy et al. (1993) discussed that RFI in itself works as a selection index. This is due to the consistency in the variance of the aggregate genotype. Therefore, the same selection response can be achieved through selection for production and DMI individually
(i.e. the components of RFI), as it would with selection on RFI directly. Due to the strong genetic dependency that exists between RFI, its component traits, and DMI, applications of RFI would likely include joint selection on RFI and its components. The selection program suggested previously utilized joint selection of DMI and RFI component traits at the index level to achieve selection objectives, thereby achieving breeding objectives with minimal data collection and computation.

Due to the high cost associated with measuring DMI in a large reference population, the feed consumed by a first parity lactating cow was chosen as the selected trait, as this is most likely to be adopted by the Canadian dairy industry. It is recognized that first lactation animals have more feed sinks, as there is an additional energy requirement for growth; however, the DMI correlation between first parity and later parity lactating cows is still stronger than that of non-lactating, growing heifers and bulls to later lactation animals (Berry et al., 2014). In addition, first parity cows represent the largest component of a milking dairy herd, and there is not the same time delay to collect records on daughters of a sire as there would be when records are taken in later parities. As expected, the majority of the total cumulative savings of feed, and associated methane, is observed during lactating periods of the production animal, as DMI is greater in these periods compared to the dry periods.

The sensitivity analysis was only conducted on feed costs as there was a restriction on the maximum genetic correlation between traits. As genetic correlations cannot exceed 1, the inclusion of them in the sensitively analysis would skew results so as to appear that economic values are more sensitive to increases than they are to decreases in genetic correlations. In general, there is a linear proportionality between both feed costs and genetic correlations (within the allowable range) and economic value, provided the values are varied in equal proportion across all life stages. Trends suggest that the economic value estimated for a unit gain in EBV for FP is reasonable and robust.
3.5.2 Trait Selection of Methane Production

With the continual selection for increased milk yield and greater DMI comes an increase in gross methane production per animal (Hegarty et al., 2007). It is difficult to overcome this undesirable correlation, and for this reason selecting directly for reductions for methane production traits, such as daily methane production, would decrease gains in per cow milk production. This would in turn compromise gains in biological efficiency, because it is well established that higher yielding cows are more efficient provided functional traits are not compromised. Bell et al. (2011) demonstrated that the higher yielding cows, selected for milk fat yield and crude protein, consumed more dry matter per day and produced less methane per kg of energy corrected milk. Therefore, in contrast to selecting for gross methane production, the strong, favorable relationship between feed efficiency and methane production can be exploited to obtain reductions in methane emission output without impacting production (Lassen and Løvendahl, 2016).

The average methane production per unit of feed consumed used in this study was 0.425 kg CO$_2$ equivalents/kg DMI. This value was based on records being collected on Canadian study farms and likely reflects the production systems in Canada. In contrast, Bell et al. (2016) determined that the amount of methane associated with feed was 0.495 kg CO$_2$ equivalents/kg DMI. This study was completed in Australia, where a combination of pastoral and total mixed ration production systems are used. Amer et al. (2017) presented a higher value of 0.583 kg CO$_2$ equivalents/kg DMI for Irish dairy systems based on research results from New Zealand, a primarily pastoral system. The difference in these values for GHG production/kg DMI is due to the differences in production systems, i.e. pastoral production systems versus intensive feeding of rations to housed cows. The high fiber diet commonly consumed by production animals in pasture-based systems is known to contribute to higher levels of methane production and methane per unit milk (Opio et al., 2013). Therefore, it
would be expected that coefficients for methane per kg DMI estimated in New Zealand and Ireland would be higher than those estimated for Australia, with estimates for Canada being lower than both.

3.5.3 Integration into the National Index

Historically (pre 1990), Canadian dairy selection indices were focused on improving production in terms of milk yield and milk solids. Over time, the importance of health and longevity have been included with increasing relative emphasis in national indices (Miglior et al., 2005). More recently, novel traits, such as mastitis and metabolic disease resistance, have been included in genetic evaluations to optimize the production efficiency of the dairy cow (Miglior et al., 2017; Van Doormaal and Beavers, 2016). As shown in Figure 1, the annual cost to feed a cow per year in Canada has increased over the past 10 years at approximately CAD $95.06/year, therefore, addition of a feed efficiency trait into the national index would be beneficial if it can help offset the increasing feed costs. Methodology developed in this study will be used to determine the economic weighting that should be applied to a DMI-based feed efficiency trait in a national selection index.

Other trait weightings in the existing indices used in the Canadian dairy industry are expressed once per lactation. However, the FP trait defined here is only expressed once per lifetime by first lactation cows. Therefore, this will need to be taken into account when integrating any new FP trait into the national index. This can be achieved through simple adjustments made to the calculated weight for the proportion of the herd in first lactation, although more sophisticated methods for accounting for different timing and expression of traits are also available (Berry et al. 2006).

Since 2011, the growth in GHG emissions produced by the agricultural industry have been attributed to an increased use of fertilizers and crop production, as livestock populations in Canada have remained stable (Environment Canada, 2016). This has been a great success
in developing a sustainable industry which trends towards efficiency. Additional emphasis on improving efficiency through selection programs that incorporate feed efficiency traits would further advocate for the enriched sustainability and economic importance of the dairy industry to Canada.

3.6 CONCLUSIONS

Reducing the amount of inefficiently used feed through genetic selection was shown to have high economic value for the dairy industry. By lowering the trait under selection (kg of feed more efficiently used by a lactating first parity cow) by 1 unit, producers are able to see competitive return over the cow’s lifetime. Overall, this study developed a model framework that can be used to determine the economic value of a feed efficiency trait and associated methane production to be used in future selection indices.

3.7 ACKNOWLEDGEMENTS

We acknowledge funding by the Efficient Dairy Genome Project, funded by Genome Canada (Ottawa, Canada), Genome Alberta (Calgary, Canada), Ontario Genomics (Toronto, Canada), Alberta Ministry of Agriculture (Edmonton, Canada), Ontario Ministry of Research and Innovation (Toronto, Canada), Ontario Ministry of Agriculture, Food and Rural Affairs (Guelph, Canada), Canadian Dairy Network (Guelph, Canada), GrowSafe Systems (Airdrie, Canada), Alberta Milk (Edmonton, Canada), Victoria Agriculture (Australia), Scotland's Rural College (Edinburgh, UK), USDA Agricultural Research Service (United States), Qualitas AG (Switzerland), Aarhus University (Denmark). C.F. Baes acknowledges funding from Alberta Innovates Technology Futures, and the Ontario Centres of Excellence (Ontario Network of Entrepreneurs ONE).
3.8 REFERENCES


CHAPTER 4: EFFECT OF SELECTION ON EMISSION INTENSITY

4.1 ABSTRACT

A recently developed methodological approach for determining the Greenhouse Gas Emissions impact of national breeding programs was applied to determine 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 output generated in comparison to the product output. 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 generating more product (i.e. increasing fat yield). The intensity value (IV) of each trait, defined as the change in emissions per unit change in trait, was calculated for each of the investigated traits. The IV trait trend of these traits was compared for the current and prospective selection index, as well as for a system with and without supply management. The overall EI of the average genetic merit Canadian dairy herd per breeding female was 5.07 kg CO$_2$e/ kg protein equivalent output. The annual improvement in EI due to the production traits of fat, protein, and milk was -0.027, -0.018 and -0.006, respectively. The functional traits, herd life and mastitis resistance, had more modest effects (-0.008 and -0.001). Overall, the current genetic trends of the investigated traits and the respective IV indicate that the Canadian dairy system is becoming more efficient with reduced GHG emissions per unit of product output value. With the future inclusion of feed efficiency in the index, this trend in efficiency should accelerate.

4.2 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 represent only a moderate fraction of the total livestock sector, increasing awareness of 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 (2016), Canada is committed to decreasing national GHG emissions by 30% of 2005 levels by 2030. Of the 723 Mt of carbon dioxide equivalents of gross emission produced by Canada in 2015, 43.92 Mt was attributed to livestock production (Environment Canada, 2016).

For animal breeding, prioritizing genetic traits based on gross outputs of methane is not optimal. Gross methane is unfavorably associated with milk yield and a targeted genetic decrease in gross methane yield per cow may result in lower feed intake. 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 DMI.

Amer et al. (2017) recommended an approach in which the intensity of emissions per unit product 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 trend of efficiency 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 selection of genetically superior animals, as shown through the decreasing number of dairy cattle in Canada and the increased volume of milk production. 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 effects of current and future breeding goals on the EI in the Canadian dairy industry.

4.3 MATERIALS AND METHODS

Emission intensity values 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 intensity value (IV). A total of four scenarios were investigated. In scenario 1, traits included in the current index were investigated. In scenario 2, we investigate traits expected to be included in a prospective index which includes total feed intake in addition to all current traits. The purpose of Scenario 2 was to show how inclusion of Total Feed Intake 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.

4.3.1 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. (2017). In the current study, GHG emissions were calculated in terms of methane production expressed in carbon dioxide equivalents (CO₂e) per unit of protein equivalents. Emission intensity, which applies to all scenarios, was calculated as (Amer et al., 2017):

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

[Equation 1]
where $\varepsilon$ is the emissions for a fixed time period (in the current study, the average breeding interval was used) across $c$ different animal classes (rearing and subsequent lactations, 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 $j$th product, and $k$ are proportionality coefficients that convert the $j$th product into milk protein equivalents (Table 4.2). The numerator and denominator of Equation 1 sum to calculate the level of emissions yield and product output, respectively.

For the current study, the emissions of replacements and breeding cows were considered to contribute to total GHG output. Emissions were calculated based on the amount of emissions associated with the total feed intake of the animal class (Richardson et al., 2017). The number of replacements per breeding female was determined to be 0.38 via the average Canadian replacement rate (Table 4.1). Total product yield was calculated by determining the average yearly production of each output converted to protein equivalents per breeding female (Table 4.1). Products were considered to be milk and its components (protein yield, fat yield and lactose yield); however, product outputs may vary and are not limited to those included in the current study.

**Table 4.1:** Constants based on the Canadian herd of average genetic merit used to calculate product and emissions outputs.

<table>
<thead>
<tr>
<th>Constants</th>
<th>Cow</th>
<th>Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Intake, kg DM</td>
<td>8660.4</td>
<td>5932.17</td>
</tr>
<tr>
<td>Number of replacements per breeding female</td>
<td>1</td>
<td>0.38</td>
</tr>
<tr>
<td>Average milk yield, kg</td>
<td>10102</td>
<td>-</td>
</tr>
<tr>
<td>Protein, %</td>
<td>3.19</td>
<td>-</td>
</tr>
<tr>
<td>Fat, %</td>
<td>3.87</td>
<td>-</td>
</tr>
<tr>
<td>Lactose, %</td>
<td>4.9</td>
<td>-</td>
</tr>
</tbody>
</table>

1Values obtained from Chapter 3
The change in EI that arises from a 1 unit change in genetic trait \( x \) has been derived by Amer et al. (2017) by taking the first partial derivative of Equation 1 with respect to genetic merit for a trait \( x \). These values are referred to as GHG intensity values. This was done via a special case of the Amer et al. (2017) method, whereby the equation was remodeled to more appropriately represent the Canadian dairy production system.

\[
IV = \frac{\delta EI}{\delta x} = \frac{1}{\Sigma y^g} \left[ \sum_i \frac{\delta \epsilon_i(x)}{\delta x} n^g_i + \sum_i \frac{\delta n_i(x)}{\delta x} \epsilon^g_i - EI^g \left( \sum_j \frac{\delta y_j(x)}{\delta x} n^g_i k_j \right) \right]
\]  

[Equation 2]

where \( \Sigma y^g \) 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 \( EI^g \) is the total GHG emissions per breeding female expressed as carbon dioxide equivalents of output at an average level of genetic merit. The first term in the brackets accounts for the change in direct emissions, \( \epsilon_i \), per change in the index trait \( x \) with a weighting to account for the number \( n^g_i \) 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 the constraints of quota, IV were calculated for a fixed number of cows while for a system with quota, the system has a fixed product output (fat).
4.3.2 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, which 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 $/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 $1.62/kg. At 5.8% non-fat and non-protein solids, payment for lactose and other solids equates to 1.62 x 0.058 = $0.094/L of milk. However, transport charges of $0.027/L are deducted, implying a net price per liter of $0.094 - $0.027 = $0.067/L, which when expressed back to milk solids gives 0.067/0.058 = $1.154/kg lactose. This resulted in the standardization values for milk components shown in Table 4.2, where assumptions were based on the component value explanation of the Producer Milk Statement (DFO 2011). 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 3.87%, 3.19%, 4.9%, respectively, across generations and production systems for all calculations. Thus, the protein equivalent output ratios were calculated for fat as 10.60/7.96 = 1.33 and for lactose to be 1.154/7.96 = 0.145. Milk has its value ratio relative to protein based on lactose and was calculated as 0.145 * 4.9% = 0.007.
Table 4.2: Constants and conversion factors used in EI and IV calculations.

<table>
<thead>
<tr>
<th>Constants</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane yield, g/ kg CO₂</td>
<td>17</td>
</tr>
<tr>
<td>Global Warming Potential, GWP</td>
<td>25</td>
</tr>
<tr>
<td>( k, \text{ fat} )^1</td>
<td>1.33</td>
</tr>
<tr>
<td>( k, \text{ lactose} )^1</td>
<td>0.145</td>
</tr>
<tr>
<td>( k, \text{ milk} )^1</td>
<td>0.007</td>
</tr>
<tr>
<td>Feed required/ kg milk component(^2)</td>
<td></td>
</tr>
<tr>
<td>Fat, kg DM</td>
<td>6</td>
</tr>
<tr>
<td>Protein, kg DM</td>
<td>3.7</td>
</tr>
<tr>
<td>Lactose, kg DM</td>
<td>2.6</td>
</tr>
</tbody>
</table>

\(^1\) in respect to protein
\(^2\) Values obtained from Amer et al. (2017)

4.3.3 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 2017). The conversion of CH\(_4\) emissions to CO\(_2\)\(_e\) in dairy cattle has been calculated in various studies from CH\(_4\) production using the ratio of CH\(_4\) to CO\(_2\)\(_e\) (O’Mara, 2006; Wall et al., 2010a). For the current study, the output of CO\(_2\)\(_e\) from feed intake in dairy cattle was estimated to be 0.425 kg CO\(_2\)\(_e\)/kg DM as per Richardson et al. (2017). This constant was calculated using the gross methane production of 0.017 kg methane/kg DMI obtained from Canadian Research Facility (Alberta 2017) and a Global Warming Potential (GWP) conversion ratio of 25:1 for CH\(_4\) to CO\(_2\)\(_e\).

4.3.4 Selection Indexes

The Canadian dairy industry has developed two indexes for the genetic evaluation of dairy cattle, LPI and Pro$. The LPI is comprised of three sub-index components. The production component is based on fat and protein traits, the durability component on herd life, mammary system, feet & legs, and dairy strength, and the health & fertility component on daughter fertility and mastitis resistance. Pro$ 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.

4.3.5 Calculating IV for index traits in a non-quota system

Out of all of the traits currently under genetic evaluation in Canada, feed efficiency, milk yield, protein, fat, herd life and mastitis resistance are the only traits with a direct impact on EI and that are not accounted for by one of the other traits with a direct impact.

4.3.5.1 Feed efficiency

It was previously determined by Richardson et al. (2017, submitted) that for every 1 unit decrease in EBV for the Feed Performance (FP) trait, there would be a 3.23 kg reduction in unnecessary feed used. Each kg of feed has an associated 0.425 kg of CO₂e produced. Therefore, emissions change per unit change in FP EBV was 1.37kg CO₂e. 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.

4.3.5.2 Production traits

A genetic improvement of production traits causes a dual effect 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 Table 4.1 and Table
4.2. Calculation of CO\textsubscript{2}e output and protein equivalents for each production traits was as follows.

### 4.3.5.2.1 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. Milk has a lactose composition of 4.9%. The amount of CO2e/ 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 CO2e/ kg DM = 1.105 kg CO2e / kg lactose). For an additional 1 kg of milk, 0.049 kg of lactose x 1.105 kg CO\textsubscript{2}e/ kg lactose = 0.054 kg CO\textsubscript{2}e 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 x 0.145).

### 4.3.5.2.2 Protein

The amount of CO2e/ 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 CO2e/ kg DM). For an additional 1 kg of protein EBV, 1.57 kg CO\textsubscript{2}e were produced. This is diluted by the generation of 1 kg protein.

### 4.3.5.2.3 Fat

The amount of CO2e/ 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 CO2e/ kg DMI). For an additional 1 kg of fat 2.55 kg CO\textsubscript{2}e is produced. This is diluted by the generation of 1.33 kg protein equivalents (1 kg fat x 1.33).
4.3.5.3 Functional Traits

4.3.5.3.1 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 x 2533.67 kg CO₂e per reared replacement = 8.36 kg less CO₂e produced. There is less of a requirement for replacements, so the average age of the herd will increase. Later parity animals produce more product output than early 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).

4.3.5.3.2 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). The average production per day is 33.21 kg milk. 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 CM cases by 1 unit increase in EBV (0.0056). The effect on product output is 231.8 kg/ case x 1.4 cases/ CM incident x 0.0056 reduction in incident/ mastitis resistance EBV x 0.091 kg protein equivalents /kg milk = 0.165 kg protein.
4.3.6 Impact of accounting for the supply management system (Scenario 1b & 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$_2$e output via herd structure (4471.49 kg CO$_2$e/ 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 equivalents 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.

4.3.7 Genetic Trends and Trait Standardization

To put the potential these traits have to reduced EI into perspective, IVs for each trait were multiplied by corresponding estimates of annual genetic gain (Table 4.3). 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”. Some traits have significantly greater genetic improvements than others per year per unit change in EBV. For FP as defined in Chapter 3, a current genetic trend was not available; therefore, a 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. 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.

Table 4.3: Trait annual genetic gain trends

<table>
<thead>
<tr>
<th>Trait</th>
<th>Trait genetic gain/year (2011-2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Feed Intake, kg DM(^1)</td>
<td>-</td>
</tr>
<tr>
<td>Milk, kg</td>
<td>120.60</td>
</tr>
<tr>
<td>Fat, kg</td>
<td>5.96</td>
</tr>
<tr>
<td>Protein, kg</td>
<td>4.80</td>
</tr>
<tr>
<td>Herd Life</td>
<td>0.67</td>
</tr>
<tr>
<td>Mastitis Resistance</td>
<td>0.49</td>
</tr>
</tbody>
</table>

\(^1\)Note that genetic trend for feed intake is a calculated estimate using values from Chapter 3

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 (CDN, 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.

\[
\text{Relative Emphasis}_i = \frac{IV_i \times SD_i}{\sum IV_i \times SD_i} \times 100
\]

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.

\[
\text{% annual reduction }_i = \frac{IV_i \times GT_i}{EI}
\]

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.

\[
\text{Total annual % reduction} = \frac{\sum IV_i \times GT_i}{EI}
\]

where variables are described as above.

### 4.4 RESULTS

#### 4.4.1 Emissions output, production output and emission intensity

The total emissions output and product output \( (\sum y^p) \) generated per breeding female in the allocated time period was determined to be 4638.72 kg CO\(_2\)e 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\(_2\)e/ kg protein equivalents \( (EI^p) \).

#### 4.4.2 Trait Intensity Values

The IVs and IV trait trend calculated for each trait with notable effect on EI for scenarios 1 and 2 are presented in Tables 4.4 and 4.5, respectively.

Under scenario 1 where total feed intake is not a trait in its own right in the breeding objective, milk had an unfavorable IV trait trend 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. Trends of trait IV (IV * annual average genetic gain) suggested that fat and protein (-0.027 and -0.018) have the largest effect on EI. The functional traits follow with herd life and mastitis 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, a 1% reduction 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 selection on a proposed FP trait.

Table 4.4: Intensity value and intensity value trait trend for scenario 1 (current index) with and without supply management

<table>
<thead>
<tr>
<th>Trait</th>
<th>Intensity value</th>
<th>Intensity value trait trend /year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Feed Intake, kg DMI</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Milk, kg</td>
<td>0.00002</td>
<td>0.002</td>
</tr>
<tr>
<td>Fat, kg</td>
<td>-0.005</td>
<td>-0.027</td>
</tr>
<tr>
<td>Protein, kg</td>
<td>-0.004</td>
<td>-0.018</td>
</tr>
<tr>
<td>Herd Life</td>
<td>-0.012</td>
<td>-0.008</td>
</tr>
<tr>
<td>Mastitis Resistance</td>
<td>-0.001</td>
<td>-0.001</td>
</tr>
</tbody>
</table>

\(^1\)Values for fat within a quota system were -0.004 and -0.025 for IV and annual IV trait trend, respectively.

Under scenario 2, where Total Feed Intake 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 milk 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 -0.001. Under a supply management system, all IV trait trend remained constant apart from 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 Total Feed Intake trait was determine to be -0.002.
Table 4.5: Intensity value and intensity value trait trend for scenario 2 (current index plus Total Feed intake) with and without supply management

<table>
<thead>
<tr>
<th>Trait</th>
<th>Intensity value</th>
<th>Intensity value trait trend /year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Feed Intake, kg DMI</td>
<td>-0.002</td>
<td></td>
</tr>
<tr>
<td>Milk, kg</td>
<td>-0.0001</td>
<td>-0.005</td>
</tr>
<tr>
<td>Fat, kg¹</td>
<td>-0.007</td>
<td>-0.044</td>
</tr>
<tr>
<td>Protein, kg</td>
<td>-0.006</td>
<td>-0.027</td>
</tr>
<tr>
<td>Herd Life</td>
<td>-0.012</td>
<td>-0.008</td>
</tr>
<tr>
<td>Mastitis Resistance</td>
<td>-0.001</td>
<td></td>
</tr>
</tbody>
</table>

¹Values for fat within a quota system were -0.004 and -0.025 for IV and annual IV trait trend, respectively.

4.5 DISCUSSION

4.5.1 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 trends can potentially be much more modest due to lower heritabilities, smaller index emphasis, and because of a relatively recent introduction or understanding of the trait as a part of the genetic evaluation process. 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, 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 the traits effects on EI (Table 4.4 and Table 4.5). 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 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 heritabilities as genomic prediction accuracies improve over time as larger training populations build up. Correlations between traits may also affect their rate of genetic improvement; therefore, traits that are favorably correlated will benefit from mutual genetic gain.

4.5.2 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 milk yield. Milk yield had positive IV and IV trait trend, suggesting that genetic improvement for greater milk production is not favorable. However, in the current model milk 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 Total Feed Intake trait was considered which required the reconsideration of emissions due to feed consumption in order to avoid double counting. This resulted in an adjustment of the IV and IV trait trends for the production traits. The IV for Total Feed Intake of (-0.002) was independent from all other traits under investigation. It is recognized that including Total Feed Intake in the index may lower the selection emphasis placed on the other investigated index traits. However, as described by Smith et al. (1989), this should have an insignificant effect on the efficiency of the index as all economically
important trait are included with the appropriate direction of selection response. Therefore, analogous genetic improvements should be achieved.

4.5.3 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 James and Brascamp (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 of 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.

4.5.4 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 increased 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.

4.5.5 Effect of variable definitions of Feed Efficiency

For the purpose of the current study, our definition of the feed trait for Scenario 2 related to a Total Feed Intake 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 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 residual feed intake trait. For example, feed associated with milk production traits (milk, fat and protein) is usually adjusted out of residual feed intake 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.

4.5.6 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 milk volume (6%) and herd life (1%) with mastitis resistance having the lowest relative weighting (<1%).

In comparison, Bell et al. (2014) investigated EI in the U.K. using a bioeconomic model. This model identified RFI (i.e. feed efficiency) as the most prominent trait to effect EI, responsible for 36% of the total improvement in emissions. 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 (2017) for Irish cattle were comparable with those of our study, with protein and fat having the highest effects (54% and 11%) and survival and calving interval following (18% and 17%). Amer et al. (2017) 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 HL traits.

In agreement with our study, Pryce et al. (2017) reported that fat (35%) had the largest effect on EI. “Feed Saved” (i.e. feed efficiency) had a comparable relative emphasis (13%) to our feed efficiency traits. Other notable effects included survival (11%) and calving interval (11%). Milk (19%) and protein (10%) had contrasting relative emphasis to those reported in our study. These differences could be due to the variation in trait definitions between the production systems.

The reported percent reductions in total EI per year achieved through genetic gain using the current and prospective index of 1% and 1.4%, respectively, were similar to results shown in other studies. Amer et al. (2017) 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).
4.6 CONCLUSION

This paper demonstrates that a genetic gain in national index traits should result in improved system 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 novel traits.

4.7 ACKNOWLEDGEMENTS

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REFERENCES


CHAPTER 5: FINAL CONSIDERATIONS

5.1 GENERAL DISCUSSION AND PROSPECTIVE APPLICATIONS

The first objective of this thesis was to determine the economic value of daily dry matter intake (DMI) and associated methane production when selecting for greater feed efficiency (FE) in a first parity lactating cow for the Canadian dairy industry. The second objective was to investigate the environmental impact of the current Canadian dairy system by calculating the industry’s Emission Intensity (EI) and determine the intensity value (IV) of each trait included in the existing and prospective national selection indexes. These objective were achieved through the previous thesis chapters.

This work was done within the scope of a Genome Canada Large Scale Applied Research Project, The Efficient Dairy Genome Project. The overall aim of this project is to increase feed efficiency and decrease methane emissions in dairy cattle through the utilization of genomics. The project is developed on four main components: data consolidation, genomics, implementation and GE³LS. By pooling international female records for feed intake and methane emission data, a large female reference population can be established which will allow for genetic evaluation to be completed for these novel traits. In addition, the societal impact of including efficiency traits in the dairy selection index will be investigated.

Chapter 2 consisted of a complete overview on the inclusion of FE and methane emissions (ME) into national breeding programs. This literature review included possible trait definitions, direct and indirect selection responses, as well as the challenges and opportunities of inclusion of these novel traits in national selection indexes. The first objective was achieved in Chapter 3 where the response to selection for a direct FE trait generated an economic value of $0.90/ lifetime which included an increase in more
efficiently used feed (3.23 kg DMI) and an associated decrease in methane production (55 g methane).

For the Canadian dairy production system, a trait definition which captures the variation due to direct feed-related efficiency with adjustments being made at the index level would be optimal for the national breeding objective. Under this breeding system, an animal that is able to better convert feed energy into milk production by targeting the energy wasted on inefficiencies in metabolism, maintenance and digestions is identified as superior. This definition of animal superiority is more clearly investigated in Chapter 3 through the “Feed Performance” trait, as a 1 kg dry matter increase of more efficiently converted feed in a first parity lactating cow. The definition and genetic prediction of the “Feed Performance Trait” still requires further work, that will be informed by the data collected as part of the broader study previously described.

An examination of the environmental impact of current and prospective index traits, objective 2, was completed in Chapter 4. The overall EI of the average genetic merit Canadian dairy herd per breeding female was 5.07 kg CO\textsubscript{2}e/ kg protein equivalent output. Traits investigated to have substantial effect of EI were efficiency traits (FP), production traits (milk, fat, protein) and functional traits (herd life and mastitis resistance). These traits were evaluated in a system with and without the restraints of supply management (Quota); which resulted in similar results. The investigated traits currently included in the national selection index had favourable impacts on EI, totalling to a 1% decrease in EI annually. This suggests that the system is trending towards sustainability and efficiency.

Improvements can be made in the accuracy of estimates reported. The values used in Chapter 3 to calculate economic values and average DMI were based on preliminary data provided from Quebec and Ontario (making up 70% of the Canadian dairy population; CDIC, 2016). Additional nation-wide data on these parameters would produce estimates.
more representative of the Canadian dairy industry by including variation in rations, feed prices, and housing systems based on geographical location. Estimates made in the current studies also included benchmarks from international sources due to the unavailability of Canadian specific values. International parameters were used to determine estimates for cost of ration for growing heifer, the probability of clinical mastitis reoccurrence and the genetic correlations for FE and ME between life stages. Although these values are not specific for a Canadian system, they do offer reasonable approximations. The U.S. has a similar production and feeding system as Canada and represents approximately 47% of Canadian exports of dairy genetics (CDIC, 2016). In addition, studies analyzing data recorded for FE and ME parameter is minimal and currently not completed for Canadian data. Therefore, the international values used offer a positive alternative that favours conservative results as opposed to exaggerated results. This was demonstrated through the results of the sensitivity analysis. A more informative test for the sensitivity analysis would be the effect on responses to selection. This analysis can be conducted once further data is available; however similar results are anticipated. Once Canadian data is available, the values can be easily updated within the models of **Chapter 3** and **Chapter 4** to provide more Canadian-specific results.

The models developed in this thesis are an alternative to the bioeconomic models previously used to calculate economic and environmental expected response to selection for various traits in animal and non-animal models (Shaloo e al., 2004; Janssen and van Ittersum, 2007; Tess et al., 1983). The methods used in the current thesis require less computational power while providing accurate estimates for trait responses associated with the expected changes in traits. Bell et al. (2015) used the bioeconomic approach method to determine the effect of index traits on GHG emissions. Results obtain for the bioeconomic model identified similar traits of comparable magnitudes as being important as those presented in **Chapter 4**. Again, in 2016, Bell et al. used the bioeconomic methodology to
compare the economic value of ME with other biological traits of economic importance. Both bioeconomic models used are computationally complex and require a large amount of information to be known. In contrast, reasonable estimates were obtained using the models presented in Chapter 3 and Chapter 4.

Emission intensity values offer index weightings based on the trait’s impact on the environment, whereas current index weights are based on the economic impact of traits. Thus, question arises as to how traits should be weighted within an index based on the desires and requirements of the system; in this case, the Canadian dairy industry. A prospective index, which includes FE, may weight this new trait in terms of economic value (Chapter 3) or environment impact value (Chapter 4). Although differences are observed in the magnitude of weightings, the two methods mutually identified production traits, efficiency traits and health and reproduction traits as receiving the highest weighting. This suggests that favourable selection responses may be achieved with either method. Smith et al. (1989) explains that if all important traits are included in the index with appropriate selection response direction, a singular trait weighting can be altered up to 50% without significant effect on the overall efficiency of the index. It is not until important traits are omitted are great differences in index efficiencies observed, as is the case when comparing scenarios 1 and 2 of Chapter 4.

An amalgamated weighting scheme that considers the economic and environmental value of traits may be the best method of incorporating traits into the future selection indexes. The economic value derived in Chapter 3 for FE can be combined with the IVs calculated in Chapter 4 to develop an appropriate weight within the selection index for FE. Additional environmental gain can be achieved by weighting a direct environmental impact trait. However, by investigating the environmental impact of each trait individually and adjusting economic weights within the index appropriately, similar responses to selection may be
achieved without the addition of a direct environmental trait. This concept of amalgamating IVs with economic weights can also be done for all of other index traits as environmentally favourable trait trends also suggest improved economic gain. This would insure that the future Canadian breeding program is not only selecting for animals that have economic efficiency, but also environmental sustainability. Further investigation is required to determine if the level of selection response would be significantly affected by the proposed weighting scheme, as this may provide further justification for not using the bioeconomic models.

Although the results of this thesis are specific for the Canadian Holstein dairy industry, the methodology developed is versatile and robust as indicated by results of the sensitivity analysis conducted in Chapter 3. The described methodology can be applied to a wide range of dairy production systems, such as pastoral-based dairy and other dairy breed herds. In addition, the methodology described in Chapter 3, which determines the lifetime value of response to selection for FE, can be applied to other traits and other species production systems. For example, the lifetime response and economic value of a direct methane yield trait could also be determined using this methodology. To do so, the average methane production by life stage, in addition to the genetic correlations between life stages and economic value of methane would be required. As well, approaches proposed by Amer et al. (2017) and adopted in Chapter 4 can be used as a standardized system to compare the sustainability of animal production systems globally. By using EI, the efficiency of current and future breeding programs can be compared.

In the future, more data is required to determine the final definition of FE to be used in the Canadian national breeding program. Once the definition is finalized, appropriate weightings within the index can be calculated by comparing the economic importance of FE with other traits currently in the index. The final weight given will also need to consider the
perception and values of the producer and the consumer. As FE and other economically important traits have positive environmental impacts, it is necessary to further investigate the role of a ME specific trait within the index and determine if the impact of including FE in the selection index is sufficient or if an additional direct methane yield trait is required. Research identifying and measuring the social costs and benefits of selecting for FE and reduced ME, for Canada and global markets, is currently underway (Efficient Dairy Genome Project Proposal, 2015). The Efficient Dairy Genome Project will also be analyzing other “omics” data to increase the reliabilities of EBVs, including Mid infrared spectroscopy data, body temperature, and rumen microbial flora.

Overall, inclusion of FE and ME into the Canadian national breeding program requires great consideration of the general impact of selection response. Further investigation of the possible trait interactions is required. Once understood, economic values and environmental weightings investigated in this thesis can be used to determine the most effective breeding objective to create a sustainable Canadian dairy industry.
5.2 REFERENCES


http://dx.doi.org/10.1017/S0003356100002750.