Greenhouse Gas Mitigation in Dairy Production Considering Incentives and Farm Heterogeneity

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Abstract

Reducing emissions from livestock production is at the forefront of the ongoing policy discourse aimed at reducing the environmental impact of agricultural emissions and achieving net zero goals. This study examines farmer incentive to adopt breeding practices with the potential to improve farm-level environmental outcomes in dairy cattle. The modelling approach accounts for region-specific agroecological variables, milk yields, farm costs, manure management practices and input use. We also examine the potential role of revenue from the sale of carbon offsets and estimate and report the abatement costs of different scenarios. We find evidence of a wide variation in abatement costs (\$479 tonne CO_2eq^{-1} - -\$830 tonne CO_2 eq^{-1}) resulting from the implementation of the various practices. Variation in outcomes across the two regions analysed was limited. We find that whilst additional revenue from the carbon offset market can change farmer incentive, maximizing the potential of these mitigation measures requires the right complementary manure management practices.

Keywords: Net zero, farmer incentives, greenhouse gas emissions, dairy, genomics.

JEL Codes: Q12, Q56, Q58.

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1. Introduction

Reducing Greenhouse gas (GHG) emissions from livestock systems is critical to reducing overall agricultural GHG emissions and achieving net zero goals (IPCC 2022; Rosa and Gabirelli, 2023). Agriculture accounts for about one fifth of GHG emissions globally (OECD, 2022). A significant proportion of these emissions – an estimated 50% - is attributable to on-farm nitrous oxide and methane emissions from the livestock sector (Lassey, 2007). Farm adaptation strategies are crucial for increasing resilience and improving environmental outcomes (Castano-Sanchez, 2022). The relevant considerations for achieving the desired environmental outcomes at the farm-level include the choice of pathway and the design of right incentives.

It is widely acknowledged that there is scope for considerable reduction in GHG emissions through practices such as breeding, manure management, feeding and other management practices (Food and Agriculture Organization, 2023; Rosa and Gabirelli, 2023). Recent policy shifts on reducing GHG emissions to achieve national environmental targets have placed renewed emphasis on the livestock sector in several countries (See for example New Zealand (Ministry of Environment, 2023), Netherlands (Van Selm et al., 2023), UK (Climate Change Committee, 2023), Canada (Environmental and Climate Change Canada, (2023)). Additionally, new opportunities have emerged for the application of novel breeding technologies to identify and select for climate friendly traits such as higher feed efficiency and low emitting cows (Nickel, 2023; Brito et al., 2020). Along with these, are markets that offer additional revenue opportunities for livestock farmers in the emerging carbon market (Solorio, 2024).

Farmer uptake of these new breeding tools and the attainment of potential benefits depends on proper incentive mechanisms (Pannell, 2017). There is also the issue of complementarities in different management practices and possible heterogeneities across different agro-ecological zones. This paper evaluates farmers' incentive to improve environmental outcomes using breeding technologies. We focus on the potential impact of breeding for novel environmental traits and the role of revenue from new carbon offset markets. Additional emphasis is placed on complementary practices such as changes in manure management. We develop bio-economic stochastic farm level simulation models for two regionally representative dairy farms in Canada. The modelling approach accounts for region-specific agroecological variables, milk yields, farm costs and input use, genomic improvement in climate friendly traits (i.e., feed efficiency, low methane) and different manure management practices.

Previous studies have evaluated strategies for reducing the environmental impacts of dairy production using farm-level simulation models (Castano-Sanchez, 2022; Rotz et al., 2020; Geough et al., 2012). Some attempts have been made to assess the impacts of different policy measures and incentives on dairy farmer decision-making pertaining to environmental outcomes (Adenuga et al., 2020; Yang et al., 2020; Lengers et al., 2013). Adenuga et al. (2020) used an optimization model to evaluate the outcomes of a nitrogen surplus tax and nutrient application standard across different clusters of farms in Ireland. The study found differential impacts of the different policy instruments based on scale of operation. Yang et al., (2020) in a study of New Zealand farmers found that price premiums exceeding 15% could offset costs of transitioning to more environmentally sustainable practices.

Perhaps more relevant to the present study, Worden and Hailu (2020) preformed an ex-ante analysis of dairy farmer adoption of genomics for improved feed efficiency. The study found that the impact of the innovation was conditional on its predictive accuracy. The authors modelled a typical Ontario dairy farm and did not account for differences in outcomes across agroecological zones/regions. The effect of additional incentives such as carbon prices was not accounted for. Boaitey et al. (2019) accounts for the effects of spatial heterogeneity and additional revenue opportunities from the offset market. The authors however, focussed on beef cow-calf producers in Canada and did not evaluate improvements in other environmentally related traits such as methane reductions. Beef and dairy systems differ with respect to management and production practices. For example, dairy production in Canada is supply managed (McLachlan and van Kooten, 2022). This has important implications for the environmental impacts of production and farmers incentive to adopt different mitigation measures (Adenuga et al., 2020). Further, the impact of agroecological factors such as precipitation and temperature may differ across production systems.

This study addresses this research gap by developing a detailed bioeconomic model that accounts for different trait improvements, agroecological effects, economic incentives and management practices. This whole farm approach used in this study allows for the systematic evaluation of the interaction between different components and outcomes (Crosson et al, 2011). Further, using a micro-level perspective allows us to account for variations in emissions and use efficiencies between farm types (Tan et al., 2022). The failure to account for important sources of heterogeneity between farms can lead to an overestimation of the adoption potential and impacts of new technologies. The paper focusses on two regions, i.e., Alberta and Ontario. These regions represent Western and Eastern Canada respectively. We generate the novel insights into the possible drivers of farm-level uptake of technological improvements in traits relevant to environmental performance and resilience. This is relevant given the role of livestock as a key source of GHG emissions and the opportunities to leverage new technologies as well as markets to meet climate goals.

The rest of the paper is organized as follows. The next section provides an overview of dairy production in the two regions. The model is described in section 3. The results of the simulation model are presented in section 4. Section 5 concludes the paper.

2. Overview

The dairy production is a key sector of agriculture in Canada. The total net farm cash receipts in 2022 totalled $8.23 billion (Canadian Dairy Information Center,2023). The largest concentration of dairy farms (81%) is located in Ontario and Quebec. There are 3298 farms in Ontario with a total population of 475200 cows and heifers. The average farm size in the province is approximately 144 cows per farm (Holstein Canada, 2023). Overall milk production in Ontario amounted to about 31 million Hectolitres. This is equivalent to about 31% of total milk production nationally. In comparison, there are 488 farms in Alberta with a total population of 128,500 cows and heifers. This implies the average herd size in Alberta is approximately 263 cows per farm (Holstein Canada, 2023). In 2021, 8.4 million Hectolitres of milk was produced representing in Alberta. This represents 9% of overall milk production in Canada (Agriculture and Agri-Food Canada, 2024). Mixed dairy and crop production are a common feature of dairy farms in Canada. These farms typically combine home-grown feed such as hay and feed grain from crop production and purchased feed to meet herd feed requirements.

3. Methodology

A representative farmer, *i*, in the *l*th region is assumed to choose a breeding and/ management practice (*k*) over a status quo practice (*b*) if:

$$\sum_{t=0}^{T=25} \beta^t \, \pi_{ikl}^t(R_{ikl}^t, C_{ikl}^t) > \sum_{t=0}^{T=25} \beta^t \, \pi_{ibl}^t(R_{ibl}^t, C_{ibl}^t) \qquad (1)$$

Where π is profit, R_{ikl} is revenue from milk sales, livestock, surplus feed, C_{ikl} is production cost (feed, labour, livestock purchases etc.), β^t is the discount factor ($\frac{1}{(1+r)^t}$). It follows that each production practice (*k, b*) is associated with their respective levels of GHG emissions. Assuming that the requisite market exists, the farmer adopting the new practice can obtain additional revenues from offsetting if it results in lower GHG emissions. Equation (1) can be modified as:

$$\sum_{t=0}^{T=25} \beta^t \, [\pi_{ikl}^t(R_{ikl}^t, C_{ikl}^t) + \tau(p_{off} \Delta GHG)] > \sum_{t=0}^{T=25} \beta^t \, \pi_{ibl}^t(R_{ibl}^t, C_{ibl}^t) \qquad (1)$$

where τ =1, if farmer participates in carbon offsets market, 0, otherwise, p_{off} is the price of carbon and ΔGHG ($GHG_k - GHG_b$) is the reduction in GHG emissions resulting from the adoption of the new practice.

This study applies a 25-year stochastic farm simulation model to estimate the impact of different mitigation measures attainable through breeding. The representative farm is modelled as a typical mixed dairy and crop operation. The model contains detailed information on milk yield, quota, on-farm cattle inventory, feed requirements, crop production, GHG emissions and net cashflow. Figure 1 is a schematic representation of the main components of the model.

Cow inventory: Milk production is determined by the farm's quota allocation. This in turn drives the farm inventory. Following Worden and Hailu (2020), we assume a quota limit of 720000 litres per year and quota change (%/year) of 0.02. The cattle herd comprises lactating and non-lactating cows (dry cows and heifers). Milk yields per cow are estimated using a monomolecular milk yield function (Lopez et al., 2015). Milk is also reported on fat and protein corrected.

Feed: Feed demand is based on cattle feed requirements for lactating and non-lactating cows. Feed supply includes purchased and homegrown feed. Annual yields are determined based on agroecological factors such as precipitation and temperature. This approach allows us to account for spatial differences in these variables across two locations i.e., Alberta versus Ontario.

Economics: The module includes an economics component that tracks the discounted net cashflow of the representative farm. Revenue sources include: the sale of milk; surplus grains; cattle; and, from participation in offset markets under the relevant scenarios. The aggregated production costs include livestock and crop production costs, and other production costs such as labour.

Greenhouse gas emissions: The model includes a detailed accounting of on-farm GHG emissions from methane and nitrous oxide sources in the addition emissions from manure management systems (solid system, liquid system, manure directly excreted on pasture). The sources of methane emissions include enteric fermentation and manure management. Direct nitrous oxide emissions from manure management are also accounted for. Greenhouse emissions are aggregated for the whole farm and converted to carbon equivalence basis using the Intergovernmental Panel on Climate Change (IPCC) factors (IPCC, 2006). The global warming potential is assumed to be 25 and 298 for methane and nitrous oxide respectively.

The representative farm in each region is initiated with a herd of 91 cows plus 44 heifers. We assume a crop acreage of 150 acres comprising 75% of owned and 25% rented land. Feed requirements for cows in the herd is based on the animal nutritional requirements. Grain production is primarily used to meet cows feed requirement. Surplus grains are sold. Annualized yield realizations are obtained with a yield function based stochastic precipitation and temperature (average degree days). Climate data realization are based on the historical distribution of precipitation and temperature in the two regions considered.

We focus on two main strategies. Firstly, an improvement in feed efficiency (Basarab et al., 2013) and low-methane cattle breeding (Oliveira et al., 2024). We assume modest improvements in feed efficiency of -0.43/kg/dry matter/day (Alford et al., 2006). Rates of reduction in methane emissions through breeding of approximately 0.75% and 1.5% are examined (Semex, 2023). Following Worden and Hailu (2020), cost of genotyping cows for higher feed efficient and low methane cows of $15 and $10 are assumed respectively.

We estimate scenarios with and without additional revenue from the carbon offset market. The effects of current and future carbon offset price scenarios based on the prevailing price of $65/tonne Co2eq and the projected price of $170/tonne Co2eq are evaluated (Government of Alberta, 2023).

Manure management systems are combined with the mitigation strategies to evaluate the effect of different combinations of measures. In total, we examine three exploratory scenarios: i.) u baseline; ii.) participation in carbon offset markets; and, iii., combination measures. For any given mitigation approach in a specific region, abatement costs are estimated as (Huber et al., 2023):

$$Abatement\ cost = \frac{net\ returns\ (k) - net\ returns(b)}{GHG(k) - GHG(b)} \quad (3)$$

where net returns are the discounted profits under the relevant scenarios from Equations 1 and 2.

Data on farm production characteristics are taken from Worden and Hailu (2020). Precipitation and temperature data are obtained from Environment and Climate Change (2022). Data on GHG conversion factors and warming potential (IPCC,2007), farm production costs, feed prices, livestock prices (Government of Ontario 2024; Ontario Dairy Farm Accounting Project 2020; Government of Alberta 2024) are also used in the analysis. Yield functions are parameterized following (Xu et al., 2020). Assumptions regarding fat and protein content of functional unit (1kg) of Milk obtained from Jayasundra and Wagner-Riddle (2014).

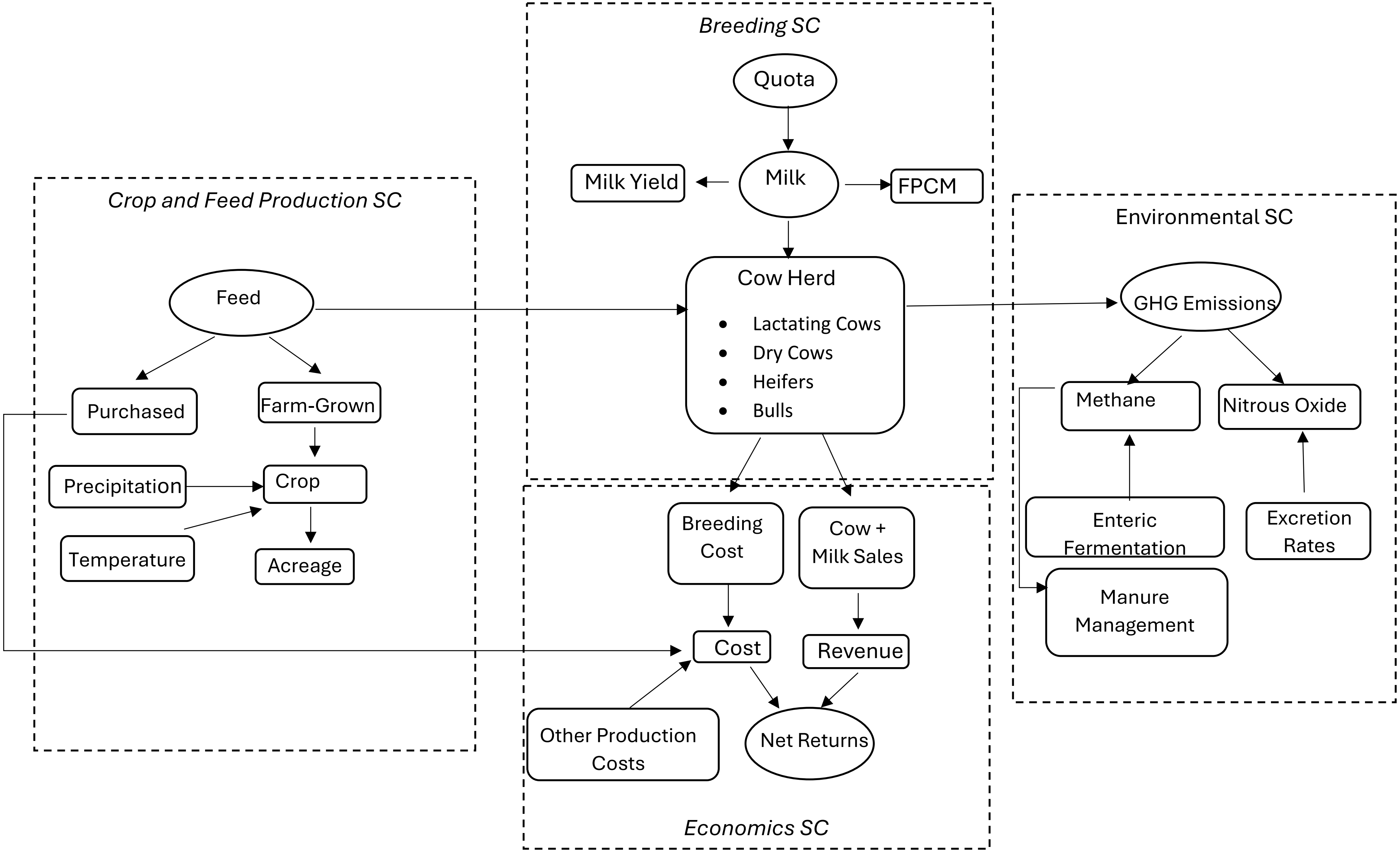

Fig. 1: Diagrammatic representation of dairy farm simulation model
Note: SC denotes sub-component

4. Results

4.1 Baseline results: Selection for improved feed efficiency and low methane

The results show variation in the economic and environment impacts of the different migration measures analysed. The selection for higher feed efficiency leads to increases of up to 40% in net returns. Higher feed efficiency is associated with reduced feed consumption and feed cost (Pryce et al., 2014; Goddard et al., 2016). Feed cost constitute 40-60% of the production cost of a typical dairy farm (Connor, 2014; USDA-ERS, 2019). The positive change in net returns reported from the analysis implies that cost savings resulting from improved feed efficiency offsets the higher cost of more feed efficient breeding stock. The increases in net returns are higher in Ontario as compared to Alberta. This is mainly due to the relative differences in feed and production costs in the two provinces. In contrast, the breeding of lower methane cows leads to marginal reductions in farm net returns of 6-4% relative to the baseline scenario. This is a result of the higher cost of the low methane cows relative to conventional cows (**Fig. 2**).

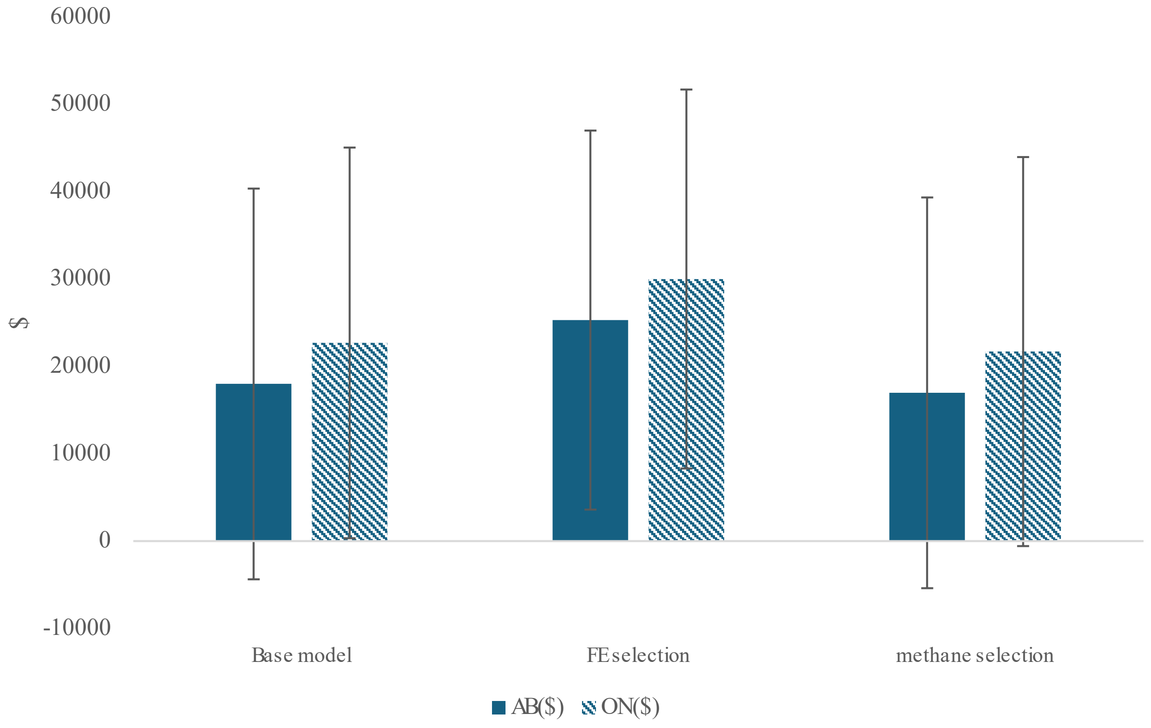

Fig. 2 This figure shows farm net returns for different selection strategies for Alberta (AB) and Ontario (ON). Error bars represent standard deviation. FE denotes breeding for higher feed efficiency. Methane selection is breeding for lower methane cows.

4.2 Abatement costs accounting for revenue from offset markets

Based on Equation 3, we report estimates of abatement costs scenarios under farmer participation in the carbon offset markets. Under this scenario, we assume that the representative dairy farmers in the two regions are able to sell emission reductions on the carbon offset market. The counterfactual is the non-participation in offset markets.

4.2.1 Breeding for higher feed efficiency

Given that breeding for higher efficiency improves net returns whilst reducing GHG emissions, the abatement costs associated with farmer uptake of the practice are negative. The magnitude of the estimate is highest under the higher carbon price scenarios (\$170tonne CO_2eq^{-1}) and lowest under non-participation in the offset market scenario (**Fig. 3**). It is further evident from the results the regional differences in abatement costs - Ontario versus Alberta - are relatively small. This is due to the structural similarities in production between the two provinces. Specifically, an identical quota limit is assumed for the two regions.

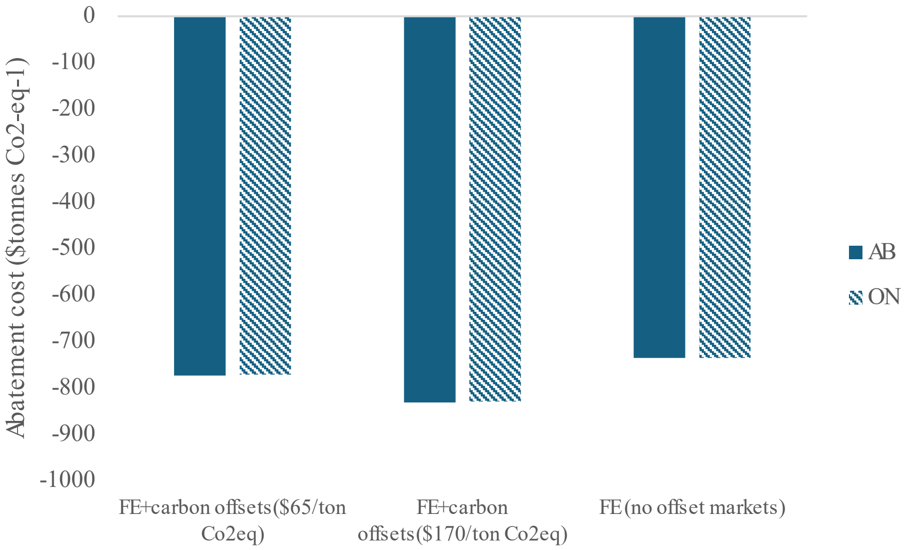

Fig 3. This figure shows the abatement costs associated with breeding for improved feed efficiency (FE) under different carbon offset price scenarios in Alberta and Ontario (\$65 and \$170/tonne CO_2eq).

4.2.2 Breeding for reduced methane

We find that participation in the carbon offset market has a higher impact on the changes in abatement costs pertaining to the selection for low methane cows as compared to breeding for feed efficiency. Breeding for low methane cows under the scenario where farmers do not participate in carbon offset schemes leads to highest abatement costs in the two regions (**Fig. 4**). These costs are higher under the low selection (0.75%) scenarios. Indeed, participation in the offset market at lower carbon market price and a breeding intensity of 0.75% yields positive abatement costs although lower than the non-participation scenario. This suggests that the revenue from the carbon scheme is not sufficient to offset the higher cost of the low methane cows given the level of emission reduction attainable. When the price of carbon in the offset market is sufficiently high (i.e., \$170tonne CO_2eq^{-1}), the abatement costs under this scenario become negative ~ -\$9tonne CO_2eq^{-1} (**Fig. 4**).

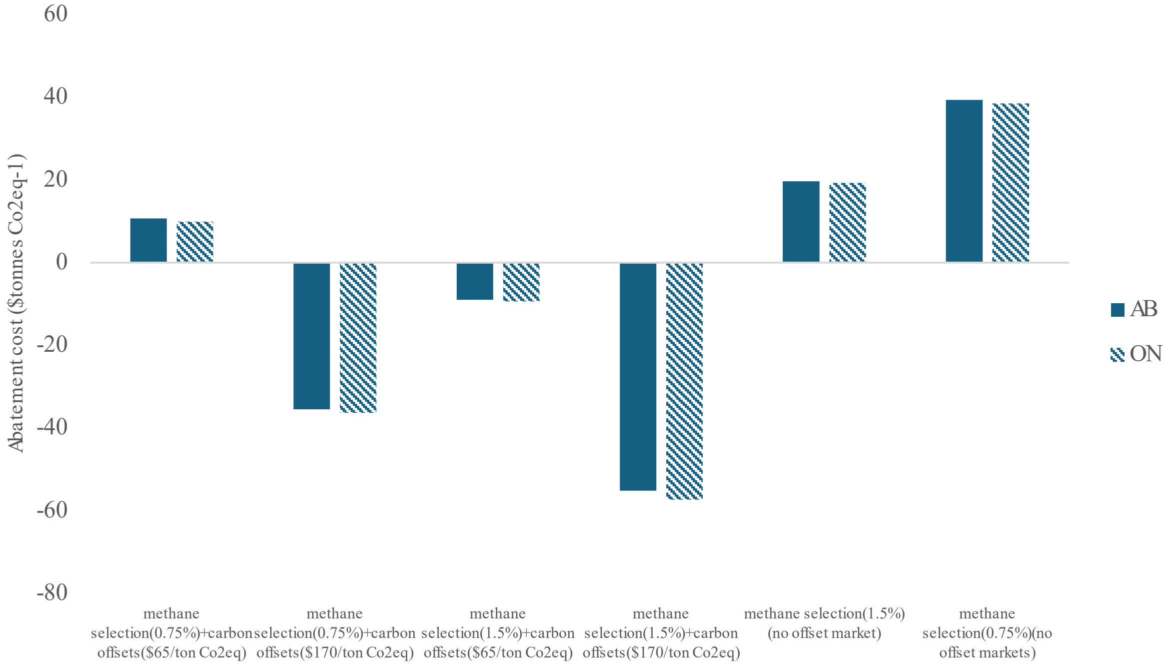

Fig 4. This figure shows the abatement costs associated with breeding for reduced methane emissions at 0.75% and 1.5% rates under different carbon offset price scenarios in Alberta and Ontario (\$65 and \$170/tonne Co_2eq).

The findings further indicate that selecting for low methane cows at higher rates (1.5%) and farmer participation in the offset market leads to negative abatement costs in both regions with the lowest cost associated with the high carbon offset price. The abatement costs estimates are -\$55.18tonne Co_2eq^{-1} in Alberta and -\$57.33tonne Co_2eq^{-1} in Ontario. The marginal regional differences are mainly driven by differences in production costs.

4.2.3 Combination of mitigation measures

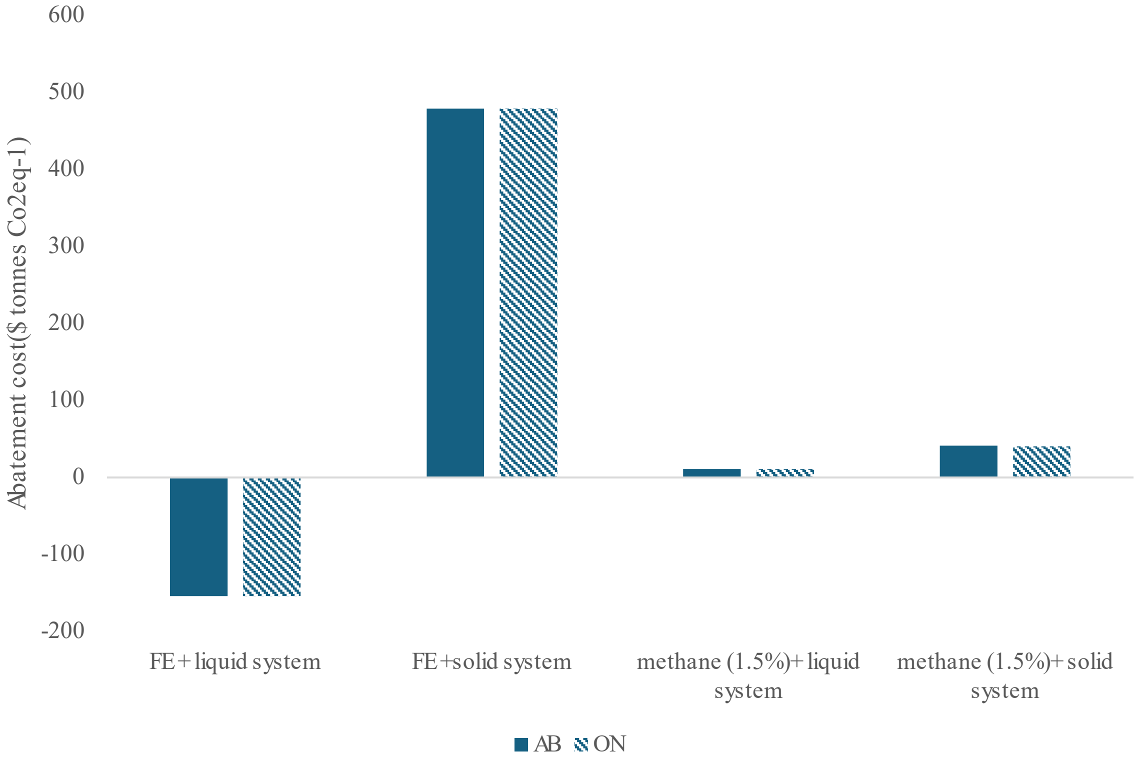

Fig 5. This figure shows the abatement costs associated with breeding for feed efficiency and reduced methane emissions at 1.5% rate under different manure systems (liquid versus solid) in Alberta and Ontario.

We explore the effect of combining different practices and farmer participation under the offset scheme (**Figs.** 5 and 6**)**. Specifically, we evaluate abatement costs for breeding for higher feed efficiency and reduced methane under two main manure management systems. Given the potential for farmers to combine multiple mitigation measures on the farm, this allows us to examine the impact of combining breeding with other on-farm management practices such as manure management. The distribution of manure management on the baseline farm was assumed to be solid (43%), liquid (40%) and on-pasture (17%). We evaluate 100% solid and liquid systems in alternative scenarios. The manure management systems have differential methane and nitrous oxide emissions (Intergovernmental Panel on Climate Change, 2006). This impacts GHG emissions and on-farm mitigation potential (Jayasundara, 2016). The results indicate that abatement costs in the two regions are highest (~ \$479tonne CO_2eq^{-1}) under the scenario where the farmer breeds for feed efficient cows and uses a solid manure management system. This implies that reductions emissions from breeding for higher feed efficient cows are not sufficient to offset the increased emissions associated with the manure management system. Relative to the baseline emissions of about 332 tonnes Co_2 eq., selecting for higher feed efficiency reduces emissions to ~ 321 tonnes Co2 eq. versus ~347 tonnes Co_2 eq. for the combined feed efficiency and solid management system approach. In contrast, abatement costs are lowest when the selection for feed efficiency is combined with liquid manure management (~ -\$154tonne CO_2eq^{-1}). From Figure 5, the impact of emissions from solid systems is lower when combined with breeding low methane cows. Consequently, the resulting abatement cost is approximately \$40tonne CO_2 eq^{-1}. This reduces to about \$10tonne CO_2eq^{-1} when selecting for low methane is combined with liquid manure systems. The implication here is that breeding for higher feed efficiency whilst implementing liquid manure management systems has a more favourable impact on cost of reducing carbon emissions relative to breeding low methane cows.

4.2.3.1 Combination of mitigation measures and offsets schemes

We evaluate the abatement costs associated with the combination practices when farmers participate in carbon offset schemes under different price scenarios. The analysis shows that the lowest abatement costs are associated with the breeding for improved feed efficiency under liquid manure management systems whilst the farmer receives revenue from the sale of carbon offsets at the higher carbon price. In contrast, Breeding feed efficient cows under solid manure systems yields the highest abatement costs. This result persists at regular and high carbon prices. This implies that emissions from solid systems are high relative to the baseline scenario and selecting of higher feed efficiency those not offset these emissions. Consequently, the farmer has no carbon offsets to sell as there are no reductions in GHG under this scenario.

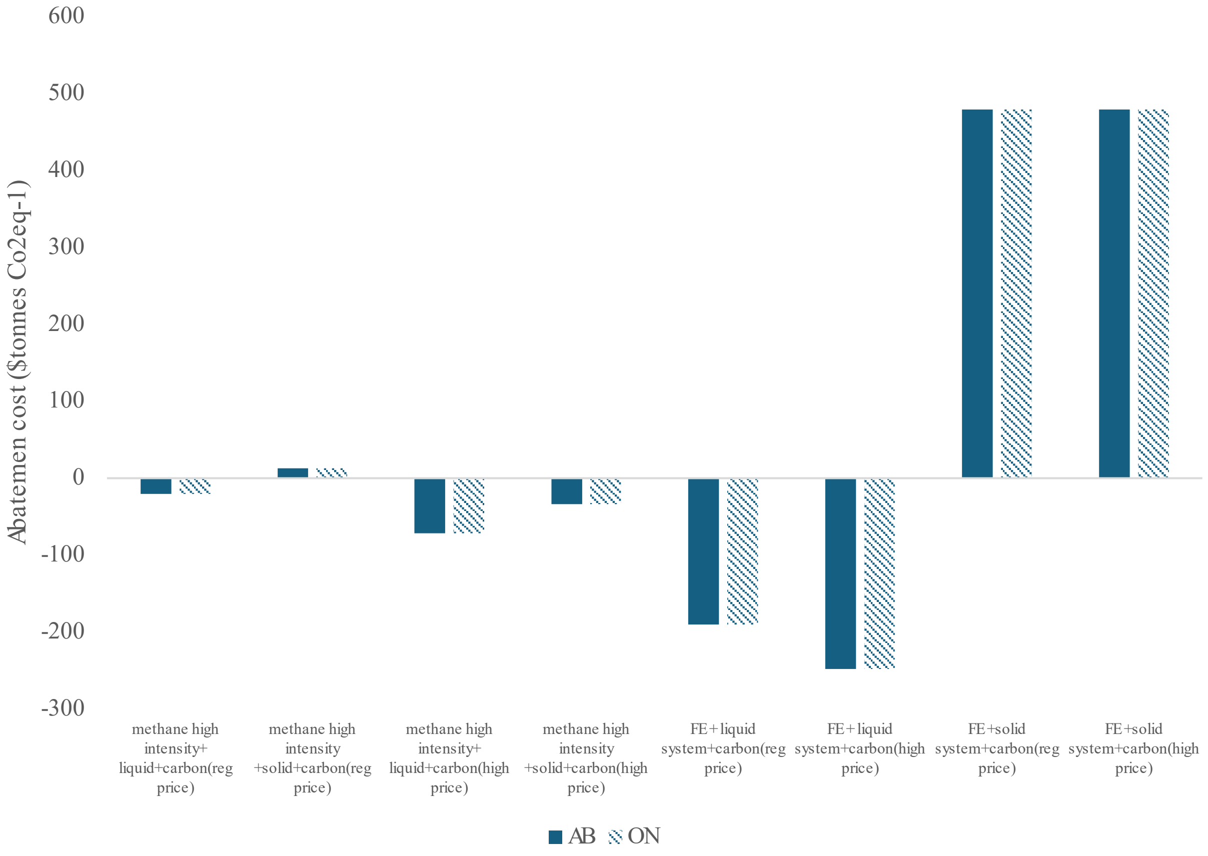

Fig 6. This figure shows the abatement costs associated with breeding for feed efficiency and reduced methane emissions at 0.75% and 1.5% rates under different manure systems (liquid versus solid) in Alberta and Ontario ($65 and $170/tonne Co_2eq).

The opportunity to participate in carbon offset markets widens the wedge between the impact of breeding feed efficient cattle and low methane cows. Revenue from the carbon offset market under the high price and liquid manure systems (and low methane selection) scenario reduces abatement costs from ~ $10/tonnes CO_2eq^{-1} (**Fig**. 5) to -$70 tonnes CO_2eq^{-1} (**Fig.** 6). The effect of carbon offset revenue on abatement is less significant for the same combination of practices under the lower carbon prices ~ $10 tonnes CO_2eq^{-1} (**Fig**. 5) versus -$20 tonnes Co_2eq^{-1} (**Fig.** 6). This result highlights the potential role of carbon pricing on farmer incentives to adopt different mitigation practices.

Figure 7 is the comparison of the various mitigation scenarios evaluated in this study. The figure indicates that the lowest abatement costs are associated with the breeding for higher feed efficiency and farmer participation in the carbon offset scheme. This implies that farmers can in fact increase net returns whilst reducing GHG emissions[1]. The highest abatement costs are association with the same practice under solid manure systems. The abatement cost estimates for breeding for low methane cows under different possible combination and carbon price scenarios and the selection for improved feed efficiency under liquid management systems are within the \$479 tonne CO_2eq^{-1} and -\$830 tonne $CO_2\,eq^{-1}$.

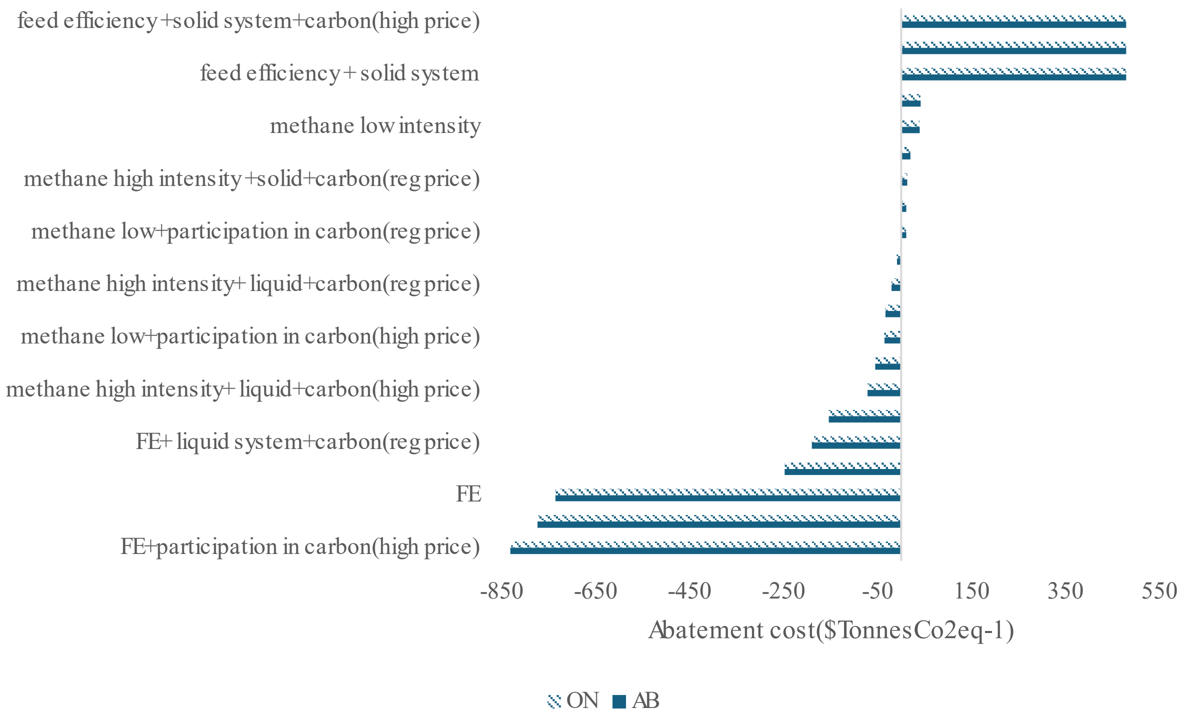

Fig 6. This Figure shows the ranking of abatement costs for the different mitigation scenarios analysed in this study.

5. Discussion and conclusions

Our results indicate that cost effective pathways exist for reducing GHG emissions and achieving net zero objectives through selective breeding for different traits. We also find the opportunity for additional revenue from the carbon offset markets can be important in incentivising farmer adoption of different practices. The emerging private and public sector initiatives in this regard (Solorio, 2024; Environmental and Climate Change Canada, 2023) may have positive impacts on enhancing environmental efficiency at the farm level.

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[1] This also applies to all scenarios with negative abatement costs.

Additionally, implementing complementary management practices of the farm can have far reaching effects. Indeed, our findings show that under certain manure management systems emissions increase relative to the baseline scenario even when farmers are breeding environmentally friendly traits. This supports the need for whole farm approaches in the implementation of mitigation approaches (Stewart et al., 2009).

The findings highlight evidence of limited heterogeneity in the impact of the different mitigation approaches and in the effect of incentives. Given the assumption of identical quota limits on the two representative farms and the economic and environmental impact of milk production levels, this result is not surprising. It shows that unlike beef cow-calf production, for example, dairy farming may be less susceptible to agroecological influences. Further, the quantitative restriction on production limits producers' responsiveness to changing agroecological conditions. This implies that depending on the level, the quantitative restrictions imposed by the quota may have positive environmental impacts (Adenuga et al., 2020). Additionally, the issues pertaining to the uniform carbon pricing mechanism across different regions (Boaitey et al., 2019) may be less relevant in this context.

Overall, selective breeding for climate friendly traits such as feed efficiency and low methane offers mitigation potential for dairy GHG emissions. Maximizing this potential requires the right complementary management practices and incentive systems. Private financing opportunities offered by the emerging carbon offset market can play an important role in this regard (Pierce and Strong, 2023).

The findings presented in this paper must be interpreted with the following caveats in mind. First, we focus on the selection for individual traits with accounting for multi-trait effects. For example, we do not account for correlations between selecting for low methane and milk yield. Considering that livestock production and breeding is inherently output driven (e.g., milk production), producers may place less emphasis on input traits such as feed efficiency irrespective of their environmental benefits (Goddard et al., 2016). Second, we do not evaluate the effects of changing quota limits on production. Given the role of the quantitative restriction on production identified in this study, varying the level of quota can have significant effects on producer incentives. These represent potential areas of research.

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