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Methane production inventory between 1960–2020 in the Finnish dairy sector and the future mitigation scenarios

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Enteric methane (CH_4) represents about half of the climatic footprint of milk production in Finland. Methane is generated from the surplus hydrogen produced during the anaerobic feed digestion process in the rumen. Methane intensity per liter of energy corrected milk (g CH_4 kg^{-1} ECM) is a function of the number of cows, milk yield (MY), replacement rate (RR), and the diet composition. This study aimed to model and report the inventory of CH_4 from milk production in Finland between 1960 and 2020. Furthermore, we report the potential future scenarios of CH_4 mitigation strategies based on the further development in MY and feed efficiency with constant or changing BW of cows. The diet composition of cattle was formulated for 5-year periods according to feed consumption statistics and the current metabolizable energy (ME) requirements for dairy cattle. The CH_4 production from cattle was simulated using the formulated diets with the Nordic dairy cow model Karoline. The future CH_4 mitigation scenarios of increased MY and improved feed efficiency were simulated using Lypsikki® dairy farm model. During the inventory period, the number of cows (1000) decreased from 1150 to less than 258, and MY increased three-fold. The total milk and CH_4 production peaked in 1965 being 3650 and 110 million kg per year and decreased to 2300 and 48 million kg per year in 2020, respectively. Consequently, decreased number of cows and increased MY reduced the total CH_4 production by 56%. In addition, CH_4 intensity improved by 36% during the inventory period. Of the future scenarios, increased MY and improved feed efficiency had a substantial potential to improve CH_4 intensity. In both scenarios maintaining the current BW of cows resulted in higher mitigation potential. We conclude that selecting more efficient animals has a significant CH_4 mitigation potential.

Key words: dairy cow, milk production, feed efficiency, modelling, greenhouse gasses

Introduction

The enteric methane (CH_4) production contributes a significant part of the total carbon footprint (CFP) of milk production (FAO 2010, McGeough et al. 2012, Naranjo et al. 2020). In Finland, the reported CFP for raw milk is around 1.0 (typical range 0.8–1.2) kg CO_2 equivalents (CO_2-e) per kg of energy corrected milk (ECM) at the current milk yield (Astaptsev 2018). Methane from enteric fermentation and manure management contributes at least half of the raw milk CFP (FAO 2010, McGeough et al. 2012), the latter being less than 10 per cent of the total CH_4 emissions from milk production in Finnish climatic conditions (Astaptsev 2018). The methane emissions from dairy production represent about 2.5% of the total greenhouse gas (GHG) emissions in Finland.

In Finland,it can be assumed that the total CH_4 production and CH_4 intensity (g CH_4 per kg ECM) from dairy production has been reduced due to increased productivity and decreased number of dairy cows. With increasing milk yield (MY) the maintenance intake is diluted to a greater milk volume resulting in lower CH_4 intensity. However, CH_4 intensity is also affected by the body weight (BW) and replacement rate (RR) of the cows, which in turn may be impacted by increasing MY. In addition, the changes in the diet composition (higher quality forages, protein supplements, increased concentrate proportion) may influence CH_4 yield as expressed per dry matter intake (DMI) and consequently affect CH_4 intensity.

The role of ruminant production in contribution to GHG emissions is intensively discussed (Steinfeld et al. 2006). The purpose of this paper is to study the development of CH_4 production from milk production in Finland between 1960 and 2020 taking in account the changes in number of cows, MY, RR, BW and in diet composition. In addition, we report the potential future scenarios of CH_4 mitigation strategies based on the further development in MY and efficiency of ME utilization with constant or changing BW of dairy cows.

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Material and methods

Replacement

Replacement rate (RR) was calculated considering the changes in the number of cows during the year as follows:

RR = Cows culled / Cows Y_1 – ([Cows Y_1 – Cows Y_0] / Cows Y_0),

where Cows Y_0 and Y_1 are number of cows in the current and previous year.

Requirements of metabolizable energy (ME) of growing heifers were calculated using the maintenance requirement of dairy cows (0.515 MJ kg^{-1} metabolic body weight [MBW = BW$^{0.75}$]) and using the mean BW during the growing period. Requirement of ME for gain (41 MJ kg^{-1}) were derived from the requirements of growing heifers (Luke 2021a). Calving weight was assumed to be 0.92 of the BW of all cows. The current requirements of pregnancy (11, 19 and 34 MJ during the last 3 months of gestation) were adjusted according to MBW relative to a 600 kg cow.

The diet of replacement heifers was comprised (g kg^{-1} dry DM) of grass silage (400) grass hay (200), grain (barley: oats 50:50; 200) and pasture (200). Diet compostion was assumed to be constant during the inventory period. Nutrient compostion of the diet was calculated according to feed table values (Luke 2021a). The formulated diet contained 133 g crude protein (CP) and 534 g neutral detergent fibre (NDF) per kg DM and 10.6 MJ ME kg^{-1} DM. Daily DM intake required to meet ME requirements was calculated by dividing the energy requirement by dietary ME concentration based on tabulated feed values (Luke 2021a).

Dairy cows

The number of cows and total milk production were obtained from official statistics (Luke 2021b). The average MY of cows was calculated by dividing total annual milk production by number of cows. This production level is lower in herds not participating in the control system than that in the controlled herds. Energy corrected milk yield was estimated as milk yield × 1.03 before 1990 when milk protein and lactose concentrations were not analysed. Body weight from controlled herds was used for all cows since the data is not available for farms not participating the cow control systems. Requirements of ME were calculated according to Luke (2021a) with 0.515 MJ ME kg^{-1} MBW for maintenance and 5.15 MJ kg^{-1} ECM for production. Requirements for pregnancy were estimated as described for replacement heifers. A safety margin of 5% was used for the total ME requirement.

Dietary ingredient composition was based on the data from the controlled herds (ProAgria 2021). Daily DM intake of dietary ingredients was calculated by dividing daily ME requirement by calculated ME concentration of the diet. It was calculated using the proportions of dietary ingredients and their tabulated ME concentrations (Luke 2021a). Before 1995 feed intake estimates in the controlled herds were calculated as net energy feed units based on starch equivalents. Feed units (FU) were converted to DM by using appropriate coefficients (FU kg^{-1} DM). From 1995 to 2010 feed intake was expressed as ME-based feed units (feed unit = 11.7 MJ ME) and from 2010 as DM intake. Predicted DM intake to meet ME requirement was adjusted to consider the associative effects of feeding level and diet composition on diet digestibility as described by Huhtanen et al. (2009). The adjustment factor increased from 1.00 to 1.04 during the inventory period due to increased DM intake and greater diet digestibility.

Recording of feed intake has changed during the 60 years' period. Until 2005 the concentrate intakes were classified as grain and protein supplements. From 2010, the concentrates are classified to grain, compound feeds, high CP compound feeds, protein concentrates, protein supplements and by-products. From 2010, the amount of protein supplements (soybean meal [SBM], rapeseed meal [RSM] and rapeseed expeller [RSE]) was calculated assuming that the proportion of protein supplements in compound feeds, high CP compound feeds and protein concentrates was 200, 500 and 1000 g kg^{-1} DM, respectively. The total amount of grain was calculated assuming that compound feeds and high CP compound feeds contained 500 and 250 g grain per kg DM. The proportion of by-products was assumed to be 300 and 250 g kg^{-1} DM in compound feeds and high CP compound feeds. A ratio of 1:1 was used for barley and oats in the grain component of diet. Protein supplements were assumed to be entirely SBM until 1985, 50:50 SBM and RSM + RSE, from 2000 to 2010 SBM (20) and RSM + RSE (80), and from 2015 entirely RSM + RSE. Equal proportions were assumed for RSM and RSE in rapeseed feeds. The by-product fraction was assumed to contain 1/3 of molassed sugar beet pulp, wheat bran and barley fibre.

Simulations

Nutrient supply and methane production were simulated by the Nordic dairy cow model Karoline that is a dynamic and mechanistic model. The model structure is described in detail by Danfaer et al. (2006) and the revisions related to CH_4 production by Huhtanen et al. (2015a). Simulation time was 280 h with 0.10 h time interval.

Because the accurate information of forage ME concentration and ingredient composition was not available, a sensitivity analysis was conducted to evaluate possible effects of forage ME concentration, the ratio of barley and oats in grain fraction and ratios of ingredients in protein supplements and by products for a 600 kg cow eating 20 kg DM d^{-1}.

Future scenarios

Different scenarios of the increase in MY and improved feed efficiency (FE) were simulated. Four different milk production levels (9000, 10000, 11000 and 12000 kg ECM/year), each with a constant BW (600 kg) or with increased BW (600, 630, 660 and 690 kg) with the four production levels, respectively. The relationship between ECM yield and BW was derived from the Finnish cow control data. The effects of improved FE were simulated using four residual feed intake (RFI) (0, –0.5, –1.0 and –1.5 kg d^{-1}) and residual ECM (RECM) yield (0, 1, 2 and 3 kg d^{-1}) in together with all ECM yield and BW combinations. The rations were formulated by the Lypsikki® model (Nousiainen et al. 2011) using the least cost option to meet nutrient requirements (ME, MP, Ca, P, Na, Mg) within the constraints of maximum DMI and minimal forage neutral detergent fibre (NDF) concentration. The ration consisted of grass silage, a 50:50 mixture of barley and oats, and rapeseed meal. The forage was a medium-quality primary growth grass silage (10.9 MJ ME kg^{-1} DM, 150 g CP kg^{-1} DM, 570 g NDF kg^{-1} DM). Tabulated values (Luke 2021a) were used for the composition and nutritive values of concentrate ingredients.

Maximum DMI potential in initial conditions (RFI or RECM = 0) were estimated by the model of Huhtanen et al. (2011) that considers animal and diet effects independently of each other. In the RECM simulations, in contrast to regular ration formulation, potential DMI was not affected by increased ECM (by definition RECM describes higher ECM yield at same DMI, BW and energy balance). In the RFI simulation the intake potential was decreased by RFI. The price of silage DM was put low that it did not influence simulations and maximised forage intake while meeting nutrient requirements.

In RECM simulations ME requirement was adjusted by multiplying the calculated ME requirement with positive RECM by the ratio of requirements:

$$\text{Ratio} = (0.6 \times \text{MBW} + 5.15 \times \text{ECM}) / (0.6 \times \text{MBW} + [\text{ECM} + \text{RECM}] \times 5.15)$$

For RFI simulations the ratio was calculated assuming that 1 kg in RFI = 11.0 MJ ME:

$$\text{Ratio} = (0.6 \times \text{MBW} + 5.15 \times \text{ECM}) / (0.6 \times \text{MBW} + \text{ECM} \times 5.15 + \text{RFI} \times 11.0)$$

In both simulations the same adjustments were made for ME and MP requirements (Luke 2021a), but mineral (Ca, P, Na, Mg) were not changed.

Results

Methane inventory 1960–2020

In Finland the total milk production was peaked in 1965 at 3665 million kg and declined steadily until 1995 (Fig. 1). Thereafter, total milk production has remained stable at about 2300 million kg. The number of cows (1000) has decreased from 1150 in 1960 to 258 in 2020, but milk production per cow has increased 3-fold during this period. For dairy cows, dietary CP concentration increased from 130 to 160 g kg^{-1} and NDF concentration decreased from 550 to 430 g kg^{-1} DM, respectively, during the inventory period.

Methane production per cow/year increased about 2-fold, from 80 to 157 kg, during 1960–2020 (Fig. 2). As a result of increased BW and DMI methane production during rearing of heifers increased from 91 to 138 kg, respectively. The total CH_4 production from milk production including replacement decreased 56% from 110000 tons (1965) to 48000 tons (2020). The average reduction was 1.5% per year. In dairy cows CH_4 yield (g kg^{-1} DMI) decreased from 24.5 (1975) to 22.1 g kg^{-1} DMI (2020) and when expressed per kg digestible organic matter (DOM) it decreased from 37.3 to 32.5 g (Fig. 3).

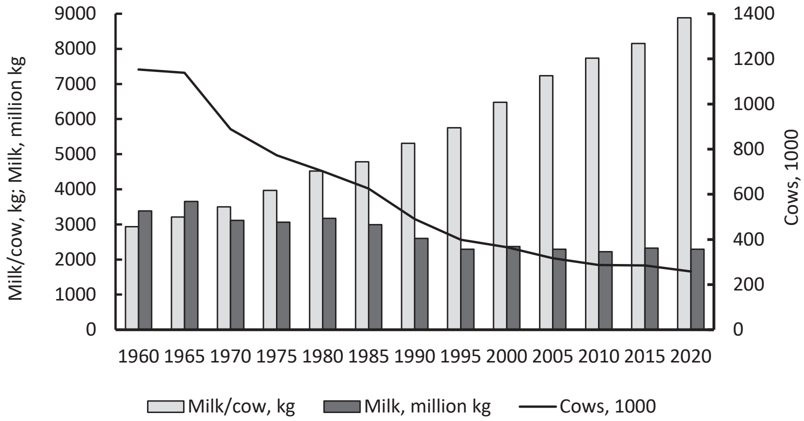

Fig. 1. Development of milk production 1960–2020 in Finland

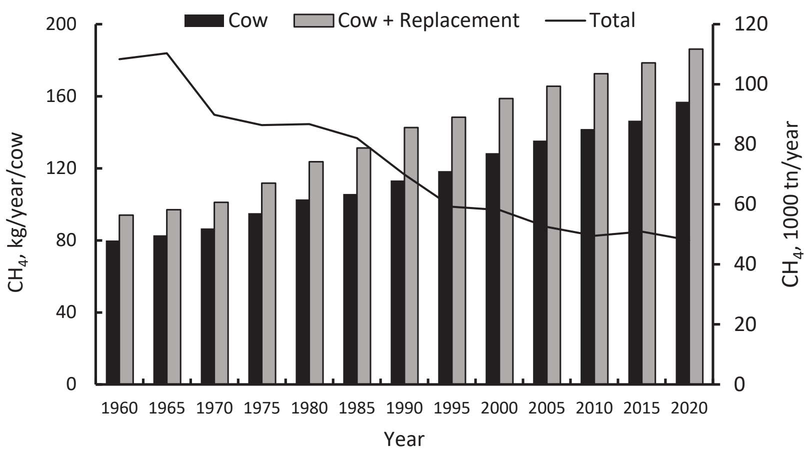

Fig. 2. Development of CH_4 production per cow/year without and with replacement (left axis) and total CH_4 production from milk production in Finland during 1960–2020 (right axis)

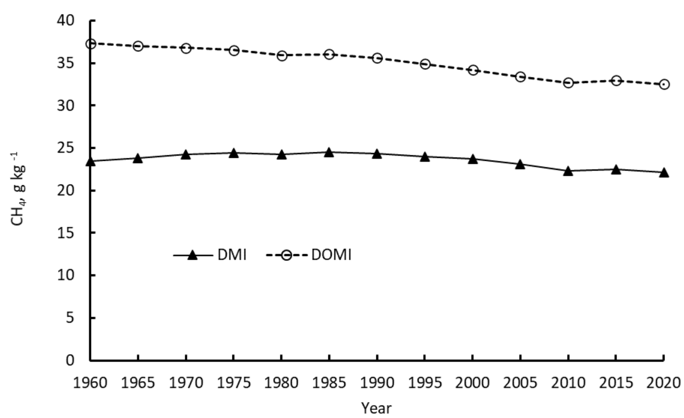

Fig. 3. Development in CH_4 yield of Finnish dairy cows from 1960 to 2020 per kg dry matter intake (DMI) and digestible organic matter intake (DOMI)

Methane intensity including replacement and dry period decreased 36% from 1960 to 2020 (Fig. 4). The reduction was on average 0.7% per year. The replacement rate of cows increased from 19 to 33% during 1970–1990 and thereafter gradually decreased to 26% in 2020. The contribution of replacement to CH_4 intensity was highest

(5.4 g kg^{-1} ECM, 20.6% of total) in 1990. Thereafter the contribution of replacement has decreased to 3.1 g kg^{-1} ECM (15.7% of total) in 2020 both due to reduced replacement rate and increased milk production level.

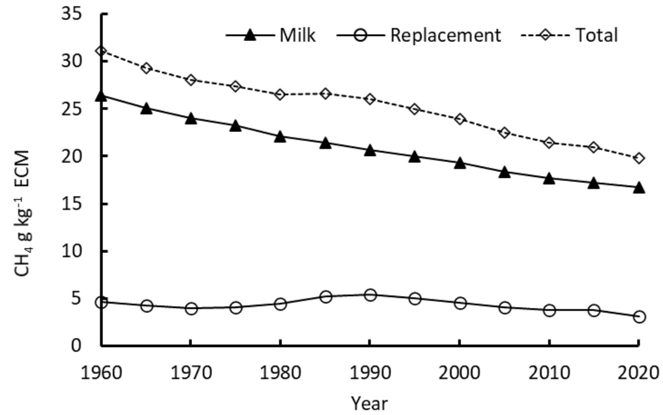

Fig. 4. Development of CH_4 production per kg ECM during 1960–2020

Sensitivity analysis

The results of sensitivity analysis are shown in Fig. 5. The effect of silage digestibility (660, 680 or 700 g digestible organic matter kg^{-1} DM) on CH_4 output was negligible, and the values were within 2 g d^{-1} range (mean simulated CH_4 production 434 g d^{-1}). Replacing barley with oats in grain mixture decreased simulated CH_4 production by 26 g d^{-1}. Similarly, replacement of RSM with RSE reduced predicted CH_4 production. Within by-products, SBP increased, and BF decreased predicted CH_4 production.

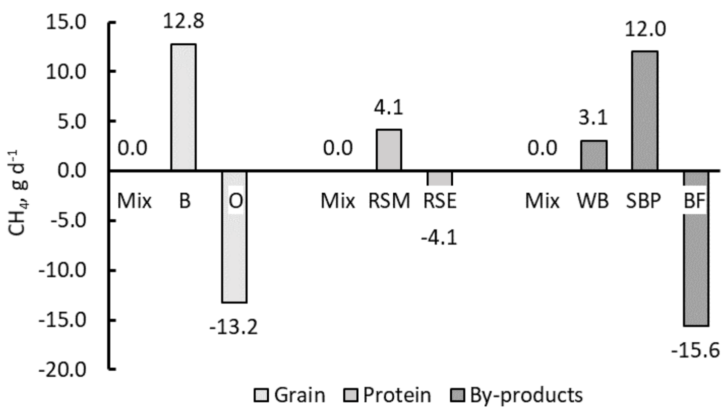

Fig. 5. Sensitivity analyses of the effects of concentrate ingredients on CH_4 production. The values are deviations from the mean simulated value (434 g d^{-1}) when only a single ingredient in feed category was used instead of mixtures. Feed ingredients: B = barley, O = oats, RSM = rapeseed meal, RSE = rapeseed expeller, WB = wheat bran, SBP = sugar beet pulp and BF = barley fibre

Future scenarios

Both increased MY and improved FE decreased CH4 intensity (Fig. 6). When BW remained constant at 600 kg with increased ECM yield CH_4 intensity decreased by 0.71 (RECM = 0) and 0.54 g CH4 kg^{-1} ECM (RECM = 3) per 1 000 kg increase in ECM yield. The effects were smaller (0.40 and 0.26 g CH4 kg^{-1} ECM per 1000 kg ECM, respectively) when the greater ECM yield was associated with increased BW according to historical ratio between MY and BW. Methane intensity decreased 0.45–0.30 g kg^{-1} RECM when ECM yield was 9 000 or 12 000 kg, respectively. When increased BW was associated with a greater ECM yield almost half (47%) of the effect of higher MY on CH_4 intensity was lost (ECM 9000–12000 / BW 600 vs. ECM 9000–12000 / BW 600–690).

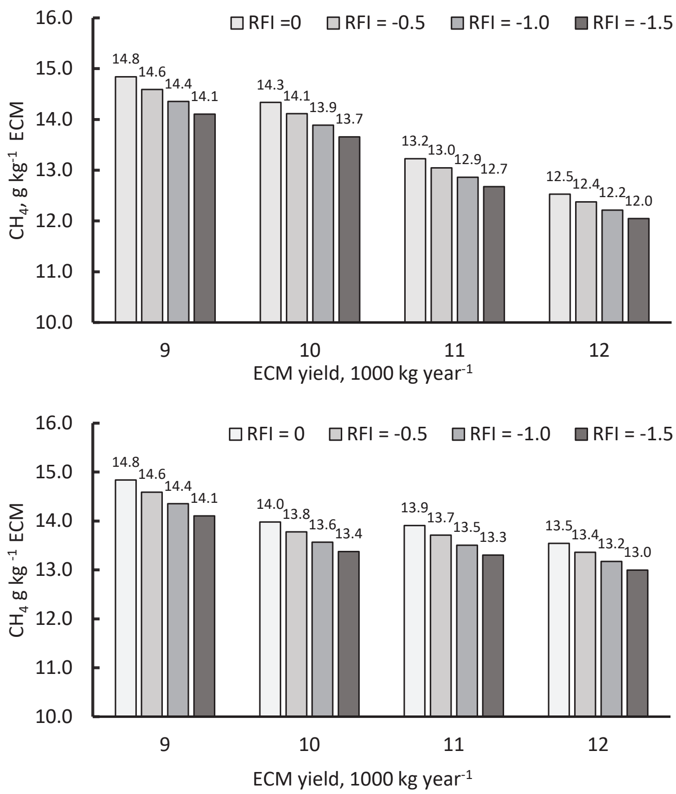

Fig. 6. The effects of increased ECM yield and residual ECM (RECM) on methane intensity (kg CH_4 kg^{-1} ECM) when ECM yield increased without (above) and with (below) associated changes in BW (30 kg per 1000 kg ECM).

When feed efficiency was improved by reducing feed intake at same ECM yield the pattern of changes in CH_4 intensity was similar to that simulated with increasing ECM yield (Fig. 7). About 50% of the potential was lost when increased ECM yield was associated with greater BW.

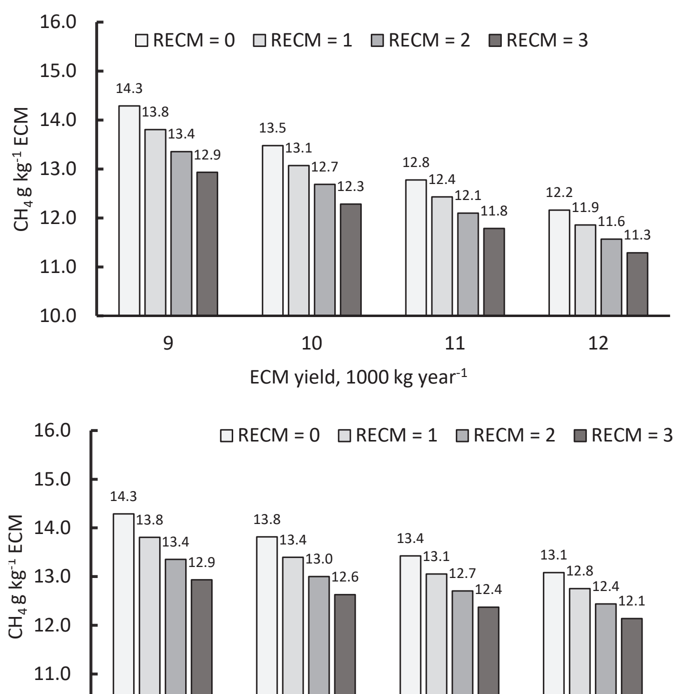

Fig. 7. The effects of increased ECM yield and reduced residual feed intake (RFI) methane intensity (kg CH_4 kg^{-1} ECM) when ECM yield increased without (above) with (below) associated changes in BW (30 kg per 1000 kg ECM)

Discussion

Methodology

We decided to use calculated energy requirements for estimating feed intake rather than intake data from controlled herds due to changes in the statistics over the inventory period. Instead, the dietary ingredient composition reported for the controlled herds was used for all cows. This may give more reliable estimates of feed intake as the on-farm recording systems are not accurate and have changed during the inventory period. The simulations were based on constant ME requirements during inventory period. However, there is some indication that maintenance requirement per kg MBW has increased (Yan et al. 1997), probably reflecting increased BW proportions of highly active liver and intestinal tissues. In comparison to current maintenance requirement of 0.515 MJ kg^{-1} MBW using a value of 0.60 MJ kg^{-1} MBW increased required DM intake 5% and increased CH_4 production by about 3%. In the simulations of future scenarios, we used the higher maintenance requirement. On the other hand, grazing has markedly decreased thereby decreasing activity requirement. The proportion of cows in controlled herds was much smaller in 1960 than in 2020. In controlled herds milk production and most likely BW are greater than in other herds. Therefore, it is possible that using BW from controlled herds overestimated BW of all cows more in 1960 compared with 2020.

There is no evidence that the efficiency of ME utilization above maintenance to milk production has noticeably changed with breeding for increased production level. The efficiency of ME utilization for milk production is positively related to the ratio ME to gross energy (AFRC 1992, NRC 2001). Increased concentrate feeding and improved forage quality have increased dietary ME concentration during the simulation period, thereby decreasing ME requirement per kg ECM. However, this effect is rather small. When calculated according to van Es (1975) an increase of 1.0 MJ kg^{-1} DM in dietary ME concentration would decrease ME requirement per kg ECM by 2%. Increased feeding level decreases diet digestibility due to shorter retention time of digesta with the effect being greater for highly digestible diets (NRC 2001). Overall, it can be concluded that the assumptions made to calculate feed intake from nutrient requirement and dietary ingredient composition could have only minor effects on the simulated CH_4 emissions in Finland. Possible errors also compensate each other; e.g., increased maintenance requirement and increased efficiency of ME utilization with improved diet quality. The data on the major components influencing CH_4 production, i.e., number of cows, ECM yield, BW, and replacement rate were derived from official statistics, and could therefore be considered reliable.

The results of sensitivity analysis indicate that possible errors in estimating dietary ingredient composition could only marginally affect predicted trends in CH_4 production. Forage quality in terms of digestibility has improved during the simulation period because of the replacement of hay and straw with grass silage that is more digestible due to earlier harvest. Diet digestibility is positively related to CH_4 yield (Ramin and Huhtanen 2013). However, the effects of forage digestibility on CH_4 yield have been variable (Beever et al. 1989, Warner et al. 2016).

Increasing dietary fat concentration decrease CH_4 production (Giger-Reverdin et al. 2003, Grainger and Beauchemin 2011) but data on the amount of supplementary fat used in dairy cow diets is not available. However, it is possible that more supplementary fat is now used in dairy cow diets than 50–60 years ago. Karoline simulations predict a 3% decrease in CH_4 production per 10 g kg^{-1} DM increase in dietary fat supplementation replacing grain in the diet.

Methane production was predicted by the Nordic dairy cow model Karoline (Danfaer et al. 2006) revised by Huhtanen et al. (2015a). In model evaluation (Ramin and Huhtanen 2015) the model predicted observed CH_4 production precisely and accurately with residuals not significantly related to main factors influencing CH_4 production. In a later analysis (Kass et al. 2022) the Karoline model predicted CH_4 production more accurately and precisely than the Molly model. Predictions of CH_4 production by Lypsikki® and Karoline models were strongly correlated ($R^2 > 0.99$) despite the models are independent of each other.

Methane inventory 1960–2020

The decrease in the number of cows and total milk production were the main factors explaining reduced CH_4 production from 1960 to 2020. In addition, CH_4 intensity improved 36%, both with and without considering replacement. A reduction of 0.7% per year in CH_4 intensity agrees with Capper et al. (2009) who reported a 0.6% reduction per year for the intensity of GHG emissions per unit product in the US over a 63-year period. Dilution of the maintenance requirement to a greater volume of milk has been the main factor for this development. Improved genetics, nutrition, and overall management have all contributed to the reduction in CH_4 intensity due to increased milk production efficiency. The yield of ECM increased about 3-fold during the inventory period. In 1960 a cow consumed 1.23 kg DM to produce 1 kg ECM, whereas in 2020 feed conversion rate was 0.82 kg DM kg^{-1} ECM. The latter value agrees with the values reported for Californian dairy herds in 2014 (Naranjo et al. 2020). Increased BW has partly counterbalanced the potential to reduce emission intensity. The cows are now about 60% heavier than in 1960 that has reduced the potential to improve CH_4 intensity due to increased BW and maintenance requirement.

Methane yield in dairy cows decreased, especially when expressed per kg DOM intake, thereby contributing to reduced emission intensity. We calculated that reduced CH_4 yield contributed 24% to improved CH_4 intensity during the inventory period. This is because increased feeding level decreases CH_4 yield (Yan et al. 2000, Ramin and Huhtanen 2013). This can be attributed to reduced diet digestibility, increased efficiency of microbial synthesis by repartition fermented carbon from volatile fatty acid and gasses to microbial cell and changes in rumen fermentation patterns.

The proportion of replacement to CH_4 intensity increased from 17% in 1960 to 24% in 1990 after which has steadily declined to 19% in 2020. The decline is partly due to reduced replacement rate and partly due to increased milk yield. Reducing the replacement rate further to 20% CH_4 intensity would decrease 0.9 g kg^{-1} ECM, i.e., about 4–5%. Bell et al. (2015) emphasized the importance of improvements in health and fertility (and overall survival) in reducing GHG emissions.

Future scenarios

Animal breeding that exploits apparent between-animal variation in CH_4 production is often proposed as a mitigation strategy that is inexpensive, permanent, and cumulative (Hayes et al. 2013). It has been shown that enteric CH_4 production is under some genetic control from by the host animal (Lassen and Løvendahl 2016). Based on respiration chamber data of 1277 sheep, estimated heritability was 0.29 ± 0.05 and 0.13 ± 0.03 for the CH_4 production (g day^{-1}) and CH_4 yield (g kg^{-1} DMI), respectively (Pinares-Patiño et al. 2013). Reisinger et al. (2021) estimated maximum mitigation potential of low-emission breeding to be 15% by 2030 with high confidence in sheep.

However, practical potential of this strategy may not be very large. In the analysis of large dataset (n = 641) from respiration chamber studies between-cow coefficient of variation (CV) in CH_4 yield was 6.6% (Guinguina et al. 2020a). Reduced diet digestibility is a significant drawback from selecting low-emitting animals. In comparisons of low- and high-emitting animals digestibility was consistently lower in low-emitting animals (for discussion see Løvendahl et al. 2018). Because lower digestibility is related to faster digesta passage rate (Pinares-Patiño et al. 2003), it might be difficult to select low-emitting animals without depression in digestibility. Digestibility is competition between the rates of digestion and passage; therefore, digestibility can be maintained only if the digestion and passage rates increase at the same time. In the study of Goopy et al. (2014) low-emitting sheep had a smaller rumen volume compared with high-emitting sheep. In New Zealand Bain et al. (2013) showed that sheep selected for low methane production had a smaller rumen than high emitting sheep. Considering the potential of reducing CH_4 production it is important to remember that the microbes, not the cow, produce CH_4. Animal characteristics related to reduced CH_4 production, reduced rumen volume and faster digesta passage rate, are against efficient utilization of non-human edible resources such as forages for human food production. Reduced rumen capacity can be a disadvantage in high-producing dairy cows fed forage-based diets due to a lower intake potential. In conclusion, a scenario of selecting animals for apparent lower CH_4 emission may not be a feasible strategy.

Considering the small variability in CH_4 yield reliable measurements of CH_4 are required for accurate predictions of breeding value. Sniffer methods are currently the only device that allows large-scale recording in on-farm conditions. However, the reliability is questionable. Between-cow CV in CH_4 measurements have been up to 3–4 times greater than in respiration chamber studies suggesting a large contribution of random variation. It has been suggested (de Haas et al. 2020) that increasing the number of repeated measurements is the most convenient method to increase reliability of prediction in Sniffer system. Unlike random errors, systematic errors, e.g., variation in exhaling rate, cannot be compensated by increasing number of observations (Wu et al. 2018). The strong correlation between head position of the cow and CH_4 concentration measured by the Sniffer and high repeatability of head position (Huhtanen et al. 2015b) may indicate that a part of the measured between-cow differences is systematic. Using CH_4/CO_2 ratio lessen the problem related to head position. However, using predicted CO_2 production leads to underestimation of CH_4 production from inefficient cows and overestimation that from efficient cows (Huhtanen et al. 2020).

Selecting for improved feed efficiency is another animal breeding strategy for mitigating CH_4 intensity. We simulated the scenarios of improved efficiency by reducing RFI from the current level (0) stepwise to -1.5 kg d^{-1} and RECM from 0 to 3 kg d^{-1}. These ranges are within observed values in several studies. Connor et al. (2019) reported a difference of 1.4 kg d^{-1} between medium and high efficiency cows in RFI in the whole lactation study. High efficiency cows (1/3) consumed 1.3 kg d^{-1} less DM (RFI) and produced 3 kg d^{-1} more ECM (RECM) than medium efficiency cows (1/3) based on the analysis of respiration chamber data (Guinguina et al. 2020b). Because of a long study period (Connor et al. 2019) or direct measurements of energy balance in respiration chambers (Guinguina et al. 2020b), the effects due to errors in estimating the contribution of body energy balance are likely to be small.

In the current simulations CH_4 intensity improved 10% when RECM increased from 0 to 3 kg d^{-1} at 9000 kg ECM production level. In the analysis of respiration chamber data, the difference between medium and high efficiency cows ranked according to RECM was 3 kg d^{-1} (14%). The smaller effect in the current study is related to the higher yield (dilution of maintenance decreases). Overall, improved CH_4 intensity with increased RECM is based on greater volume of milk from the same feed intake. If both production level and efficiency are improved simultaneously, substantial improvements in CH_4 intensity can be achieved. For example, increasing ECM yield from 9000 to 11000 kg ECM and efficiency from 0 to 3 kg RECM would improve CH_4 intensity by 17.5% if BW does not increase. The effect is less (13.3%) if BW follows observed trends with increased ECM yield. Improved CH_4 intensity is partly related to dilution of maintenance feed to greater volume of milk (1), less production feed required per kg ECM (2) and reduced CH_4 yield with increased feed intake (3). With increased ECM yield without changes in efficiency predicted CH_4 yield decreased 0.46 g kg^{-1} DM per 1000 kg increase in ECM yield at constant BW. However, if the BW of cows increases with ECM yield following the previous trends, predicted change in CH_4 is much smaller (0.18 g kg^{-1} DM) per 1000 kg ECM. With these scenarios total CH_4 production at farm or country level will only decrease if the number of cows is reduced.

Reduction in replacement rate by 1 %-unit decreased CH4 intensity 0.16 g kg^{-1} ECM, based on 2020 values of CH_4 production of replacement heifers and lactating cows. In addition to improved CH_4 intensity in milk production, also beef production benefit of increased longevity in integrated milk and beef production systems. More calves will be available for beef production and also more beef inseminations can be used for dairy cows.

Compared with the direct selection of low-emitting cows to improve CH_4 intensity, selection for improved feed efficiency has several advantages. It increases the profit of milk production in terms of reduced feed cost (RFI) or increases production at the same intake (RECM), whereas breeding for low emissions is unlikely to influence production economy. A reduction of 10% in CH_4 production increases ME intake by about 2.4 MJ d^{-1} (DM intake 20 g d^{-1}) if feed intake and digestibility do not change. Assuming an efficiency of 0.62 for the efficiency of ME utilization in lactation and that 50% of additional ME is used for milk production, expected increase in ECM yield is 0.24 kg d^{-1}. Data from studies investigating the effects of 3-nitroxypropanol does not indicate increased production although decreases in CH_4 production have been about 25% (Van Wesemael et al. 2019, Melgar et al. 2020). With improved feed efficiency also the manure production per unit of milk decreases thereby reducing N_2O and CH_4 emissions from manure. Bell et al. (2015) estimated that the contribution of N_2O was 34% of animal related CO_2-e. Improving feed efficiency also decreases CO_2-e per unit of product. With improved feed efficiency less field is required to produce given amount of milk leading to reduced emissions of CO_2 and N_2O.

Conclusions

Enteric CH_4 production of dairy cows including replacement in Finland has decreased by 56% during 60-year period from 1960 to 2020. A reduction of 36% (0.7% per year) was found for CH_4 per unit of product. The reduction in total CH_4 production was partly exlained by a 77% reduction in the number of cows. Improvements in the efficiency in milk production trough breeding, feeding and management all contributed to the decrease in emission per unit of product. These trends observed between 1960–2020 are likely to continue in the future, but with a slower rate because of diminishing potential of diluting maintenance feed to higher milk yield. Selecting cows for improved feed efficiency is the most sustainable strategy to reduce emissions per unit of product. With improved feed efficiency the profit of milk production may increase due to reduced feed cost and/or increased milk yield from the same feed input. In addition to reduce enteric CH_4 emissions improved efficiency decreases manure output and consequently N_2O and CH_4 emissions, and GHG from feed production per unit of product. With direct selection of low-emitting cows economical and other environmental benefits are negligible compared with breeding for improved feed efficiency.

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