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Modelling effects of different milk production intensities on methane production and nitrogen excretion when targeted amounts of milk and beef are produced

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The objective of the study was to model the effects of different milk production intensities on methane (CH_4) production and nitrogen (N) excretion of cattle in Finnish milk and beef production when the targeted amount of milk and beef is produced. Beef production strategies at current annual milk production in Finland (2 200 million kg) were optimised by Excel Solver for each combination of milk yield (8 000, 9 000, 10 000, 11 000, and 12 000 kg year^{-1}) and beef production (60, 65, 70, 75, 80, 85, 90, 95, and 100 million kg year^{-1}). Increased milk production intensity decreased total CH_4 production at each beef production level. In addition, at the lower levels of beef production than currently (85 million kg) total manure N output decreased with increased intensity of milk production but at current or higher beef production levels the effects of milk yield were small. The current strategy of producing milk and beef with high milk production intensity seems to be effective in terms of CH_4 production and N emissions.

Key words: dairy cattle, beef cattle, beef production, environmental impacts

Introduction

The role of livestock production in the future food systems has been the subject of intense public and academic debate (see e.g. Kuhmonen et al. 2024). Livestock production is a significant contributor to environmental impacts (Leip et al. 2015, Herrero et al. 2016), and especially ruminants contribute to methane (CH_4) emissions (Johnson and Johnson 1995, Beauchemin et al. 2020). Cattle production also has a significant environmental impact through nutrient surpluses of arable land that potentially result in eutrophication (Nousiainen et al. 2011, Hietala et al. 2021). On the other hand, in climatically unfavourable areas where growing crops for food is not possible or economically feasible, grass-based cattle production is an important component of sustainable agriculture because of the ability of cattle to transform feeds not suitable for humans into high-quality food (Godfray et al. 2010, Kuhmonen et al. 2024).

In the Finnish food system, the dairy industry has played an important role for more than a century (Kuhmonen and Kuhmonen 2023). There are currently approximately 230 000 dairy cows in Finland and 2 174 million liters of milk were produced in 2023 (Luke 2024a). Although livestock production, and in particular ruminants, have a significant environmental impact on food production, it is noteworthy that enteric CH_4 production of dairy cows have been significantly reduced in Finland over the past years. Recently, Huhtanen et al. (2022) modelled that 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 in CH_4 intensity (CH_4 g kg^{-1} energy corrected milk [ECM]). The reduction in total CH_4 production was partly related to reduction in the number of dairy cows (77%) and partly to reduced CH_4 intensity from improvements in the efficiency in milk production through breeding, feeding and management all contributed to the decrease in emission per unit of product (Huhtanen et al. 2022).

Finnish beef production is mostly based on dairy breeds. In 2023, a total of 262 251 cattle were slaughtered in Finland and 85.4 million kg of beef was produced (Luke 2024b). Of the beef produced, 44% came from dairy and dairy × beef breed bulls, 21% from dairy cows, 14% from dairy and dairy × beef breed heifers, 12 % from beef breed bulls, 5% from beef breed heifers and 3% from suckler cows (Luke 2024b). One key difference to most of the milk and beef production countries is that soybean meal or maize silage are not used in Finnish cattle production, whereas grass silage and cereal based feeding has a key role in cattle feeding (Hietala et al. 2021).

In recent years, the decrease in the number of dairy cows has diminished the supply of calves for beef production originating from dairy herds, and therefore, there is a discrepancy between the demand and supply of domestic beef in Finland (Hietala et al. 2021). In 2023, beef self-sufficiency was approximately 90% (Luke 2024b).

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Efforts have been made to respond to the situation by increasing the slaughter weights of bulls and heifers and increasing the number of suckler cows. However, both procedures are likely to increase the environmental impact of produced beef. In general, beef production based on dairy herds has been shown to produce less greenhouse gas (GHG) emissions per produced meat unit compared to beef production from suckler cow systems (Casey and Holden 2006, Nguyen et al. 2010, Flysjö et al. 2012, Hietala et al. 2021). Huhtanen and Huuskonen (2020) reported that increasing slaughter weights of dairy breed bulls increases CH_4 emissions per kilogram of beef produced. The greater feed intake and declining live weight gain (LWG) were the main contributors for the increased CH_4 intensity (more CH_4 kg^{-1} carcass weight gain) with increased live weight (LW) (Huhtanen and Huuskonen 2020).

The objective of the present study was to model the effects of different milk production intensities on the CH_4 production and N excretion of cattle in milk and beef production when the target is to produce a certain amount of domestic milk and beef. It was hypothesized that if the targeted amount of milk could be produced with a lower intensity a larger number of dairy cattle would be available for beef production. This would mean a smaller number of suckler cows and the possibility of reducing slaughter weights when the target is to produce a certain amount of beef. It was hypothesized that this could reduce the overall environmental impacts of milk and beef production, even if emissions from milk production alone would increase with an increase in the number of dairy cows and a reduction in the intensity of production.

Material and methods

Diet formulation and environmental emissions for dairy cows

The diets for dairy cows were formulated to meet the feeding recommendations of Luke (2024c) for metabolizable energy (ME), metabolizable protein (MP), and minerals (Ca, P, Mg and Na) with the following modifications: 0.6 MJ kg^{-1} metabolic body weight (MBW) was used as maintenance requirement and ME discount at production level of intake was adjusted to 50% predicted by Luke (2024c) equation. The adjustment was based on reduced CH_4 and urinary energy losses with increased feed intake. The diets were formulated of grass silage, energy supplement (mixture of barley, oats and molassed sugar beet pulp: 0.40:0.40:0.20), protein supplement (mixture of rapeseed meal and rapeseed expeller: 0.50:0.50), calcium carbonate and sodium chloride. The least cost diets were optimized for annual milk yields ranging from 7 500 to 12 500 kg (500 kg increments) for a 650 kg cow using Lypsikki® model. Milk fat and protein concentrations were 44 and 35 g kg^{-1} at each production level. Feed prices were set to maximize forage intake and minimum level of protein supplement. Maximum dry matter (DM) intake (DMI) was constrained by the model of Huhtanen et al. (2011) that considers both animal and feed factors independently of each other. Based on average calving interval of 403 d in controlled herd and assuming dry period of 60 d the cows were lactating for 311 and dry for 54 d $year^{-1}$. During dry period a mixture of grass silage and barley (0.80:0:20) were used to meet the requirements for maintenance and pregnancy.

Methane emissions and faecal N output were predicted by the Nordic dairy model Karoline (Danfaer et al. 2006, Huhtanen et al. 2015). Urinary N output was calculated as N intake – Milk N – Faecal N assuming zero N balance. The effects of production level on CH_4 emission and N output (kg cow^{-1} $year^{-1}$ or g kg^{-1} milk) were estimated by linear regression or power function model.

Diet formulation and environmental emissions for suckler cows and growing cattle

For suckler cows, the diet was standardized to meet the suckler cow feeding recommendations which are mainly based on those for dairy cows (Luke 2024c). On average the annual diet included grass silage (400 g kg^{-1} DM), pasture grass (400 g kg^{-1} DM), oats (100 g kg^{-1} DM) and straw (100 g kg^{-1} DM). Methane emissions and faecal N were predicted by the Karoline model. Manure N of beef cows was assumed to the same as N intake. Retained N was taken into account in carcasses.

For growing dairy bulls, modelling was based on the data which Huhtanen and Huuskonen (2020) used when modelling the effects of carcass weight and dietary concentrate and protein levels on CH_4 production and N and P excretion of bulls fed grass silage-based diets. For bulls over 6.5 months of age, the data comprised in total 84 bulls, which were fed total mixed ration *ad libitum*. The three concentrate proportions were 300, 500 and 700 g kg^{-1} DM fed without or with rapeseed meal supplementation. Results for feed quality, feed and nutrient intake and animal performance have been reported in detail by Huuskonen et al. (2007). For the modelling growing period before 6.5 months of age, data from an experiment reported by Huuskonen et al. (2011) were used. The data comprised in total 120 calves which were fed in a typical Finnish system. Feed characteristics and animal performance have been reported in detail by Huuskonen et al. (2011).

Methane emissions and faecal N output were predicted by the Karoline model. Although the model was originally developed for predicting nutrient supply in dairy cows, it can also be used to predict absorption of nutrients in growing cattle (Huhtanen and Huuskonen 2020). The mean DMI and adjusted LW during the 28-day experimental periods were used as input data. The adjusted LW (LW_{adj}) at the beginning and end of different periods was estimated by the Gompertz model from the age of animals and recorded LW to smoothen the effects of random variation in daily LWG: $LW_{adj} = A \times Exp\ [-Exp\ \{1 + k \times (T – t)\}]$, where A = Asymptotic adult LW (kg), k = maximum growth rate (1/d), T = time at inflection and t = time (d). In addition to observed data, the scenarios for two additional 28-day periods were modelled using LW predicted from the parameters of the Gompertz model. The LWG for each period was computed by dividing the difference between initial and final LW by the length of experimental period. Intake during two additional periods was predicted from the model: DMI (kg d^{-1}) = $a \times LW_{adj}^{\ b}$, where a = coefficient (kg d^{-1} per kg $LW_{adj}^{\ b}$), b = exponent of LW. The parameters were estimated from observed DMI and LW_{adj} during the 12 experimental periods.

Faecal N output was predicted by the Karoline model (Huhtanen et al. 2015). Retained N was estimated using the equation of AFRC (1992): Retained N (g d^{-1}) = $[LWG \times (168.07 – 0.16869 \times LW + 0.0001633 \times LW^2) \times (1.12 – 0.1233 \times LWG) \times C] / 6.25$, where LW and LWG are as defined above, and C is the correction factor. A factor of 1.2 for large breeds was used for the modern Ayrshire bulls, since the LW of Ayrshire cows is close to 650 kg (e.g. Puhakka et al. 2016). Urinary N was calculated as N intake – Faecal N output – Retained N, all expressed as g d^{-1}.

For growing beef breed bulls, the modelling was carried out similarly to that for dairy bulls, with the difference that feed conversion for growth was assumed to be more efficient than for dairy bulls (coefficient 0.85). This was based on literature (Huuskonen et al. 2017), current Finnish feeding recommendations for growing cattle (Luke 2024c) and previously collected datasets (Huuskonen and Huhtanen 2015). For growing heifers, the same feed conversion for growth was assumed as for dairy bulls because 89% of the heifer meat produced in Finland comes from either dairy × beef breed crosses or pure beef breeds, and their energy requirement is approximately the same as in dairy bulls (Luke 2024c).

Calculations

Beef production strategies at current annual milk production in Finland (2 200 million kg) were optimised by Excel Solver (Fylstra et al. 1998) for each combination of milk yield (8 000, 9 000, 10 000, 11 000 and 12 000 kg $year^{-1}$ cow^{-1}) and beef production (60, 65, 70, 75, 80, 85, 90, 95 and 100 million kg $year^{-1}$). Maximum carcass weight was constrained to 400, 450, 325 and 350 kg for dairy bulls, beef bulls, dairy heifers, and beef heifers, respectively. Current average carcass weights of 295 and 341 kg were used dairy and beef cows, respectively. Values of 0.25 (dairy cows) and 0.175 (beef cows) were used as a replacement rate.

Methane emission and manure N (MN) output for dairy and beef cows were calculated as:

CH_4 or MN (tons $year^{-1}$) = (N × Cow CH_4 or MN (kg $year^{-1}$) + RR × Heifer CH_4 or MN) × 0.001 (ton kg^{-1}), where N = number of cows, Cow CH_4 or MN and Heifer CH_4 or MN = CH_4 or MN per cow and replacement heifer, and RR = replacement rate.

For beef breed animals (dairy and beef bulls and heifers) CH_4 emission and MN output was calculated as: CH_4 or MN (tons $year^{-1}$) = (N × CH_4 or MN (kg $year^{-1}$) × 0.001 (ton kg^{-1}), where N = number of animals and CH_4 or MN = CH_4 emission or MN output for respective animal group. Second degree polynomial regression equations were developed to predict relationship between carcass weight (kg) and cumulative CH_4 emissions or MN output. Carcass weight was estimated from periodic LW assuming the following relationship between carcass weight and LW:

Carcass weight = 0.465 + 0.000095 × LW

Sensitivity analysis

Sensitivity analysis was conducted to evaluate the effects of parameter values on CH_4 emissions and MN output at current milk (2 200 million kg $year^{-1}$) and beef production level (85 million kg $year^{-1}$). Estimated coefficients of CH_4 emissions and MN output were multiplied by 0.90, 0.95, 1.00, 1.05 and 1.10. The effects of replacement rate was estimated using 3–5 lactations (0.5 increments) for dairy cows and 4–8 calvings for beef cows (1.0 increments).

Results

Methane emissions and manure N output

Predicted total CH_4 production including dry period per cow increased as a result of increased feed intake and milk yield, but CH_4 intensity decreased from 19.7 to 14.4 g kg^{-1} milk (Fig. 1). Methane yield decreased from 22.4 to 20.5 g kg^{-1} DM intake as feed intake increased. The following linear relationship between milk yield and CH_4 production was estimated from the predictions:

CH_4 (kg $year^{-1}$) = 100.3 + 6.49 × milk yield (1 000 kg $year^{-1}$)

For growing dairy bulls, the relationship between carcass weight (CW, kg) and CH_4 was quadratic:

CH_4 (kg $year^{-1}$) = 11.38 - 0.0432 × CW + 0.000784 × CW^2

Predicted values of CH_4 production were 98.4 kg $year^{-1}$ for beef cows, and 138.3 and 155.9 kg $animal^{-1}$ for replacement dairy and beef heifers, respectively.

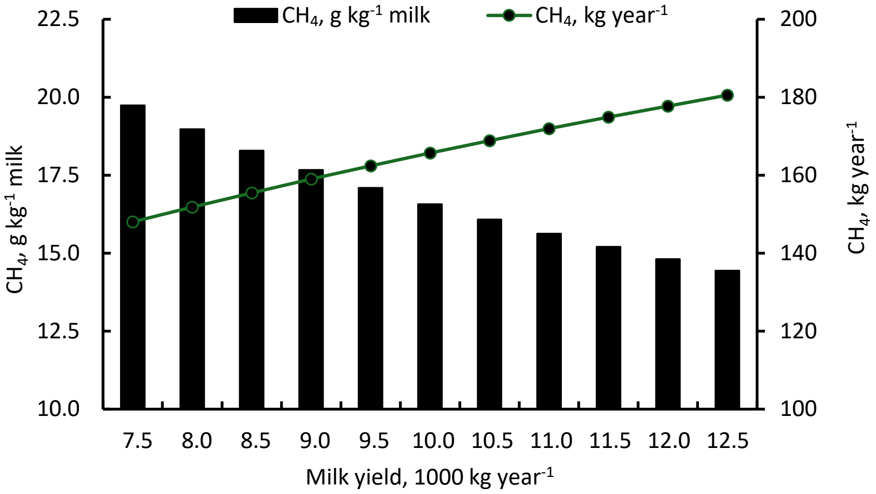

Fig. 1. The effect of milk yield on total CH_4 production and CH_4 intensity

In dairy cows predicted N output in milk and faeces increased with milk yield whereas urinary N output remained rather constant. Milk N efficiency increased from 252 to 321 g kg^{-1} N intake including dry period when milk yield increased from 7 500 to 12 500 kg $year^{-1}$ (Fig. 2).

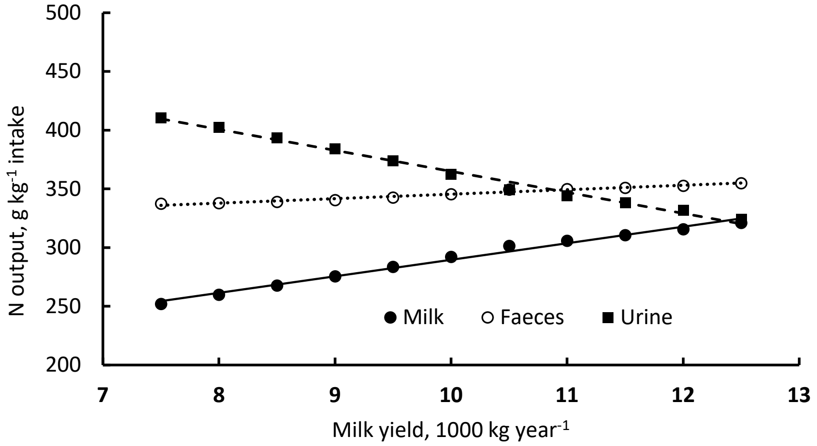

Fig. 2. The effects of milk yield on distribution of N intake

With increased milk yield the proportion of N intake excreted in faeces remained rather constant, whereas the proportion of urinary N decreased. In formulated diets, dietary CP concentration was rather constant (156–159 g kg^{-1} DM), but metabolizable protein concentration calculated according to Luke (2024c) system increased from 89 to 98 g kg^{-1} DM with increased milk yield as grass silage was gradually replaced with energy and protein supplements. The following relationship between milk yield and MN output was estimated:

$$\text{MN (kg year}^{-1}\text{)} = 90.5 + 4.49 \times \text{milk yield (1 000 kg year}^{-1}\text{)}$$

For growing dairy bulls, the relationship between carcass weight (CW, kg) and MN was quadratic:

$$\text{MN (kg year}^{-1}\text{)} = 9.43 - 0.00282 \times \text{CW} + 0.000627 \times \text{CW}^2$$

Predicted values of manure N production was 83 kg year^{-1} for beef cows, and 116.1 and 127.7 kg animal^{-1} for replacement dairy and beef heifers, respectively.

Sensitivity analysis

Replacement rate of dairy cows. Reducing the replacement rate from 33% (3 lactations) to 20% (5 lactations) decreased predicted total CH_4 emissions by 165 tons, corresponding to 0.24% of the emissions at target productions of 2 200 million kg milk (yield 10 000 kg year^{-1}) and 85 million kg beef. With improved longevity the number of slaughtered dairy cows decreased, and the proportion of dairy cow beef decreased from 25 to 15% of the total beef production.

Replacement rate of beef cows. The effect of replacement rate was modelled for 4–8 calvings (replacement rate from 12.5 to 25%). As a result of the reduced replacement rate, predicted CH_4 production decreased 387 tons (0.05% per 1 %-unit decrease in replacement rate). The decreased replacement rate did not affect the number of beef cows. Methane production from replacement heifers decreased more than it increased from larger number of slaughtered heifers resulting in a small net decrease.

Calving percentage of beef cattle. Increasing calving percentage in beef herds from the current 85 to 95% predicted decreased total CH_4 production 527 tons that relates to –0.07% per 1 %-unit increase in calving rate. The decrease in CH_4 production was related to an increased number of beef bulls and heifers and reduced carcass weight of dairy and beef bulls.

Dairy cows. Due to the greatest contribution to the total CH_4 production predicted CH_4 production was highly sensitive to changes. When predicted CH_4 production changed from 90 to 110% compared with the default equation predicted CH_4 production increased 7 296 tons (0.53% per 1 %-unit of change). However, the level of CH_4 production from dairy cows did not affect optimal strategies to produce targeted amounts of milk and beef.

Growing animals. When CH_4 production per animal varied from 90 to 110% of the default values total CH_4 production decreased 2 369 (0.17%), 881 (0.065%), 469 (0.034%) and 208 (0.015%) tons for dairy bulls, dairy heifers, beef bulls and beef heifers, respectively. These changes did not affect optimal strategies to produce given amounts of milk and beef. When CH_4 production was changed simultaneously for all growing cattle total CH_4 production decreased 3 700 tons (0.27% per 1 %-unit change), but optimal strategy was not affected.

Overall, the effects of changes in estimated CH_4 production from different animal types did not change optimal strategies to produce targeted amounts of milk and beef.

Methane emissions

Increased milk production intensity decreased total CH_4 production at each targeted level of beef production. However, the effect of milk yield was stronger at lower levels of targeted beef production, decreasing from 5 624 to 1 024 tons as the total beef production increased from 60 to 100 million kg (Fig. 3). At the current beef production level (85 million kg) the effect of milk production intensity was rather small (1 126 tons; 1.7%). Increasing the intensity of milk production first increased the carcass weight of dairy bulls and heifers. After the upper constraints of carcass weight of these animals were achieved, the remaining of the targeted beef must be produced from specialized beef herds.

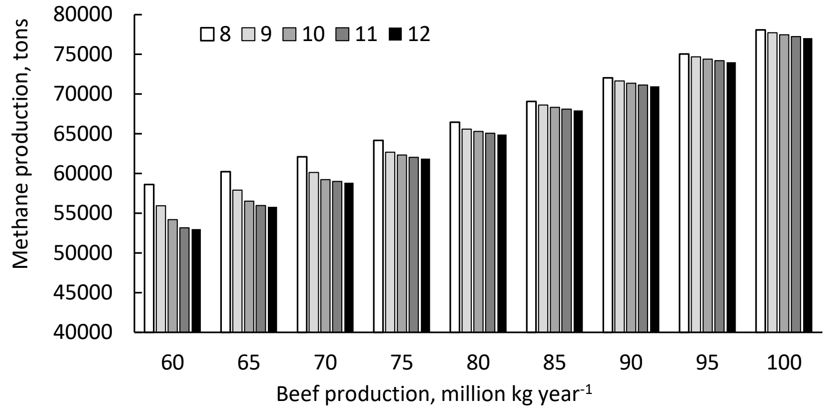

Fig. 3. The effect of milk yield (1 000 kg year^{-1}) required to produce 2 200 million kg year^{-1} and total beef production (million kg) on annual methane production

The number of required beef cows increased with increasing milk yield of dairy cows and the amount of targeted beef production (Fig. 4). Each incremental million kg beef at 10 000 kg year^{-1} milk yield had required 2 960 additional beef cows when targeted beef production was above 70 million kg. When the only strategy to increase beef production at targeted milk yield was increasing the number of beef cows the incremental CH_4 production was 607 g kg^{-1} beef.

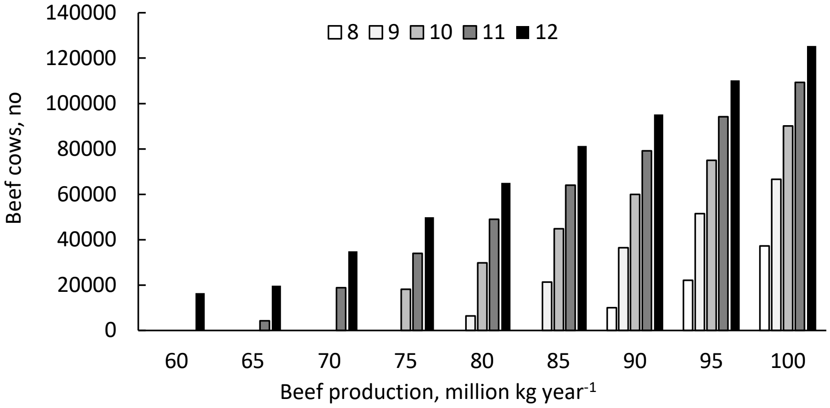

Fig. 4. Number of beef cows required to produce given amount of beef at different milk production intensity (1 000 kg year^{-1}, total milk production 2 200 million kg)

The proportion of beef from dairy cows decreased with increased milk production intensity and targeted total beef production with inverse changes in the proportion of beef from beef breeds (Fig. 5). The proportion of beef from dairy bulls and heifers was rather stable at the lowest milk production intensity and decreased with increased total beef production at the expense of beef from specialized beef herds.

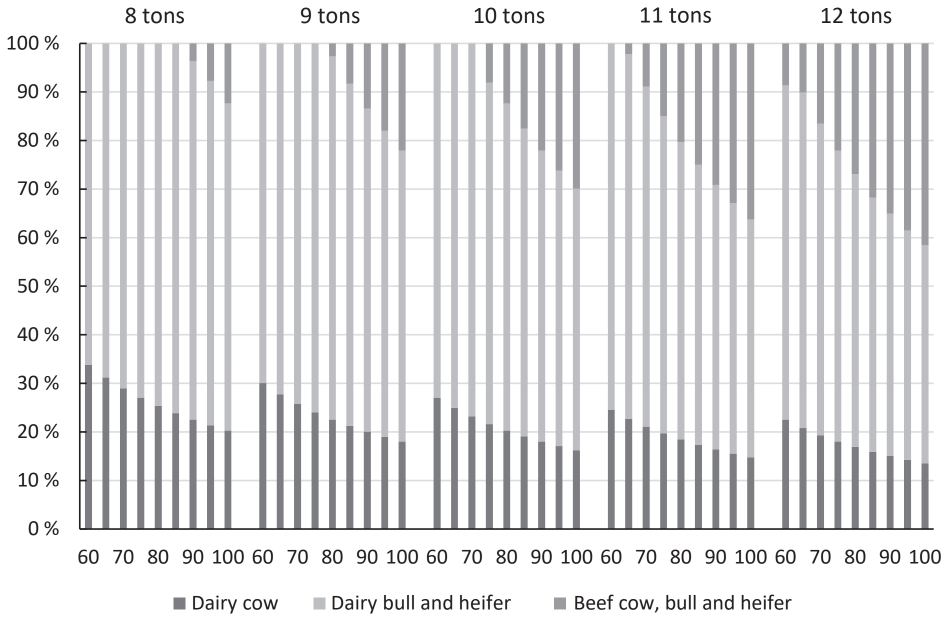

Fig. 5. The effect of milk production intensity (from 8 to 12 tons) and total beef production on the distribution of different beef types

Manure N output

Manure N output decreased with the intensity of milk production at targeted amounts of beef production (Fig. 6). The pattern of changes was like that in predicted CH_4 production. The negative effect of milk yield on MN output was greater at lower levels of beef production decreasing from 6 258 tons (14.8%) to 1 184 tons (1.9 %) when targeted beef production increased from 60 to 100 million tons year^{-1}. At the current milk and beef production levels the effects of different production strategies were small (1 609 tons; 2.9%). The pattern of changes in distribution of beef types (dairy cows, dairy bulls and heifer, total beef breeds) and the number of required beef cows required to produce targeted amounts of beef were similar to those observed for CH_4 production (Fig. 4 and 5; results not shown). The proportion of beef from dairy cows decreased with increased intensity of milk production, the proportion of dairy bulls and heifers was rather stable at the lowest milk production intensity and decreased with increased total beef production at the expense of beef from specialized beef herds.

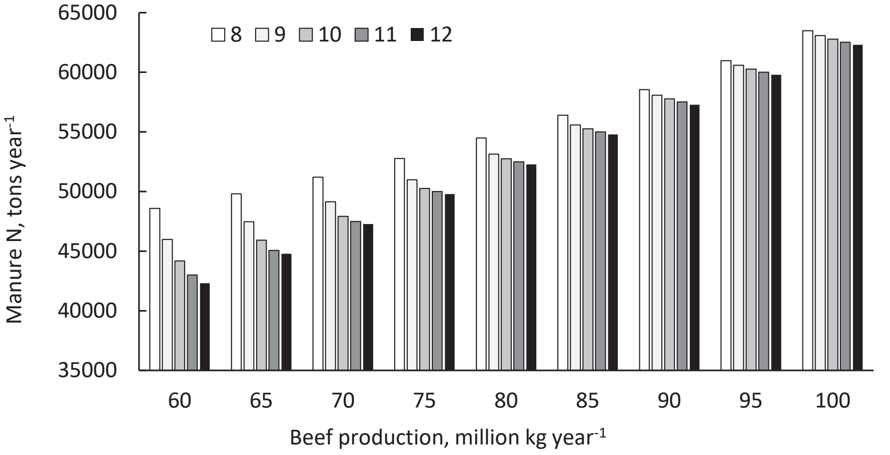

Fig. 6. The effect of milk yield (1 000 kg year^{-1}) required to produce 2 200 million kg year^{-1} and total beef production (million kg) on annual manure N output

Feed intake and feed conversion rate

The total DM requirement to produce 2 200 million kg of milk decreased with increased intensity of milk production at each level of beef production (Fig. 7). The effect was strongest at the lowest level of beef production. At current production levels of milk and beef the intensity of milk production had only minimal effects on DM requirement. The proportion of forage DM in the total DM decreased from 0.75 to 0.55 when milk yield increased from 8 000 to 12 000 kg year^{-1}. At higher milk production levels, the proportion of forage in total DM increased with increased specialized beef production.

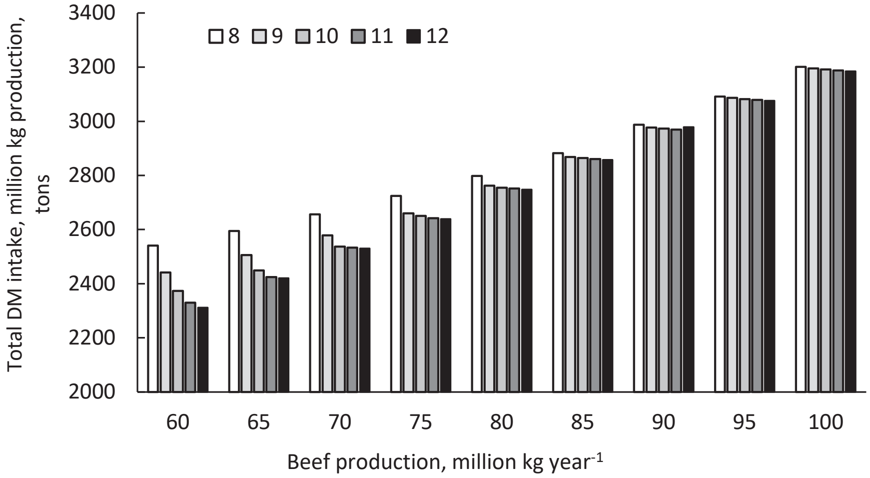

Fig. 7. The effect of milk yield (1 000 kg yea^{r-1}) required to produce 2 200 million kg year^{-1} and total beef production (million kg) on the amount of feed DM

Feed conversion efficiency decreased with increased milk production intensity and level of beef production (Fig. 8). Feed conversion efficiency in milk production, including replacement decreased from 1.027 to 0.832 kg DM kg^{-1} milk (from 1.077 to 0.873 kg DM kg^{-1} ECM). At constrained carcass weights, feed conversion efficiency was better for dairy bulls and heifers compared with beef animals (10.0 vs. 21.8 kg kg^{-1} carcass weight). Feed required for dairy replacement was included in feed conversion efficiency of milk production.

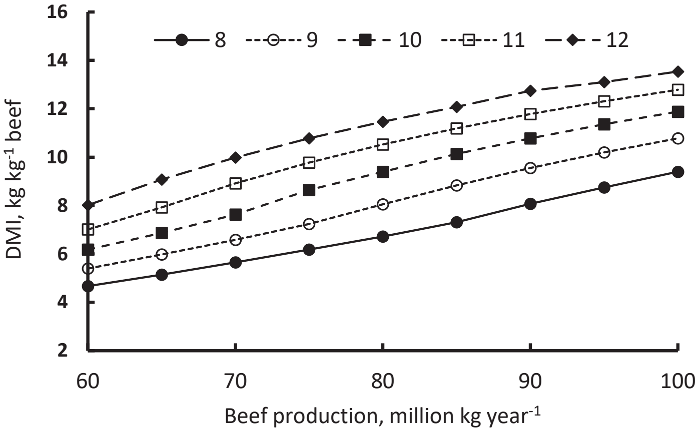

Fig. 8. The effect of milk yield (1 000 kg year^{-1}) required to produce 2 200 million kg year^{-1} on feed conversion rate

Discussion

Methane

In the present study, the Karoline-model was used because it has been shown to predict total CH_4 accurately and precisely from respiration chamber data (Ramin and Huhtanen 2015). In the later analysis with a larger dataset the Karoline model predicted CH_4 production better than the Molly model (Kass et al. 2022). The model of Niu et al.

(2018) predicts lower CH_4 production than the Karoline model, probably because of the lower NDF concentration and greater proportion of maize silage-based diets in their dataset. However, it is important to note that the level of CH_4 production from dairy cows had only marginal effects on optimal strategies to produce current amounts of milk and beef in Finland.

The sensitivity analysis using the coefficients below 1.00 for dairy cows could be interpreted as the effects of improved biological efficiency of milk production. In the analysis of respiration chamber data (Guinguina et al. 2020) CH_4 intensity was 11 and 24% lower for the best third of the cows ranked according to residual feed intake or residual ECM yield compared with the poorest third of the cows. About 1/3 of the difference in CH_4 intensity was found in the metabolizability of the diet and about 2/3 was related to improved efficiency of ME utilization for maintenance and milk production. In agreement with longitudinal analysis of Finnish dairy production (Huhtanen et al. 2022), the current analysis indicates that improvement in production efficiency of milk production is a sustainable strategy to reduce CH_4 production without sacrificing the efficiency of total ruminant production in terms of total CH_4 emissions.

Methane intensity decreased with increased DMI because of dilution of maintenance requirement to greater volume of milk and decreased CH_4 yield. Predicted CH_4 production increased 15.2 g kg^{-1} DMI with increased feeding level which is in good agreement with 14.5 g kg^{-1} DMI estimated from international database (Niu et al. 2018). When DMI is expressed as g kg^{-1} LW predicted CH_4 yield decreased 0.18 g per 1 g kg^{-1} LW increase in DMI that is slightly less than reported by Ramin and Huhtanen (2015) from the analysis of respiration chamber data. In the current study, CH_4 intensity decreased 0.28 g kg^{-1} milk that is less than 0.43 in individual cow dataset from respiration chamber studies (Carneiro de Souza et al. 2024). The lower value in our modelling is at least partly due to the higher milk yield than in the respiration chamber data. Increased yield has a stronger effect on CH_4 yield at lower production levels. When compared with experimental data our model predicted changes in CH_4 production are in good agreement, and therefore the effects of improved production are not likely to be severely biased. However, in short term the production responses to increased feed intake are less than predicted from nutrient requirements since with increased feed intake part of the incremental ME is partitioned to body tissues. In a long run, with improved genetics, nutrition and management milk production responses are likely to follow those based on ME requirements.

Possibilities to decrease CH_4 emissions by diet manipulations compared with the current diets used for Finnish dairy and beef cattle are rather limited. Replacement of barley with oats has decreased CH_4 production (Ramin et al. 2021) but quantitatively the potential is limited. Using rapeseed products with higher fat concentration or other plant oils decreases CH_4 production. In Finnish studies (Bayat et al. 2018, 2021, Razzaghi et al. 2022, Halmemies et al. 2023) increased fatty acid intake decreased CH_4 emissions by 120 g kg^{-1} increase in fatty acid intake. This is equivalent to 3.3 kg CO_2-ekv. However, the carbon footprint of plant oils is usually greater than that of grains that oils replace in the diet, for example. Schmidt (2015) reported that carbon footprint of rapeseed oil was 3.1 kg CO_2-ekv. Therefore, the net effects of oil supplementation carbon footprint are less than the reduction in CH_4 production.

Replacing grass with cereal grains is another alternative for dietary manipulation of CH_4 emissions. However, with practical ranges of concentrate proportion in dairy cow diets the effects are relatively small. The model of Sauvant and Giger-Reverdin (2009) predicted maximum CH_4 yield at 35% concentrate on a DM basis and moderate decreases of between 35 and 60% of concentrate. Cabezas-Garcia et al. (2017) reported equal total CH_4 production and CH_4 intensity when high digestibility grass silage was gradually replaced with increasing proportion of low digestibility silage and barley.

Nitrogen

At the lower levels of beef production total manure N output decreased with increased intensity of milk production but at current or higher beef production the effects of milk yield were small. Livestock manure is an environmental concern because livestock manure generates nitrous oxide (N_2O) and ammonia (NH_3) emissions, and nitrate leaching into soil and ground water, contributing to air, water, and soil pollution (FAO 2002). Environmentally, urinary N is more harmful than faecal N as is it more susceptible to evaporation and leaching losses than faecal N. In dairy, the predicted efficiency of utilization of feed N (milk N/N intake; MNE) increased with milk yield and the proportion of urinary N of manure N decreased. In our simulation, MNE improved from 252 to 321 g kg^{-1} with increased milk yield. Generally, it is assumed that MNE is improved with increased milk yield due to reduced maintenance costs (Tamminga 1992). However, when the annual milk yield exceeds 7 500 kg, only small progresses in MNE can be expected from increased milk yield (Tamminga 1996). In our study, N intake during dry period was included in MNE calculations which has the same dilution effect as the maintenance cost. The effect was even greater in manure output per kg^{-1} milk when N intake of replacement heifers was considered. Predicted manure N loss decreased from 19.3 to 14.5 g kg^{-1} milk as milk yield increased from 8 000 to 12 000 kg year^{-1}. In addition, the proportion of environmentally more harmful urinary N in manure N decreased with increased milk yield.

Manure N losses can be influenced by dietary manipulation to much greater extent than CH_4, mainly by changing dietary CP concentration. Although increased protein supplementation has a positive effect on milk production, MNE decreases and MN output increases. Kebreab et al. (2001) reported linear increases in faecal and milk N output and quadratic increase in urinary N with increased N intake. In agreement with this, Huhtanen et al. (2008) estimated that 67% of incremental N intake was excreted in urine. Low (11–13%) marginal production responses of milk protein to increased protein supplementation (Huhtanen et al. 2011) and high true CP (≥ 90%) digestibility also indicate that a large proportion of supplementary protein is excreted in urine. Protein supplementation may have opposite effects on manure N output and CH_4 emissions. Small improvements in CH_4 yield and intensity were observed with rapeseed cake supplements (Gidlund et al. 2015, 2017) but at the expense reduced MNE.

In growing cattle, the production responses to supplementary protein are generally smaller than in dairy cows. Based on a meta-analysis of the growing cattle feeding experiments, Huuskonen et al. (2014) found that increasing dietary CP concentration significantly increased LWG, but the response was quantitatively small (1.4 g per 1 g kg^{-1} dry matter DM increase in dietary CP concentration) in grass silage-based diets. The efficiency of N utilization (N retention/N intake) decreased by 1.02 g kg^{-1} per 1 g kg^{-1} DM increase in dietary CP concentration (Huuskonen et al. 2014), which indicate a poor utilization of supplementary protein in growing cattle, and consequently increased N emissions. Therefore, omitting protein supplements from the diet is often the best nutritional strategy to reduce manure N output of growing cattle fed grass silage-based diets (Huuskonen et al. 2014, Huhtanen and Huuskonen 2020). However, if a shortage of protein limits DMI and digestibility, CH_4 intensity (g kg^{-1} milk or beef) will increase.

Farm-level impacts

Although total CH_4 emissions and manure N output decreased with more intensive milk production at each beef production level, the effects were quantitatively small. In CH_4 production the relative difference between 8 000 and 12 000 kg milk yield ranged from 9.6 % (8 000 kg milk, 60 million kg beef) to 1.3 % (12 000 kg milk, 100 million kg beef). At the current production levels of milk and beef the maximum difference in predicted CH_4 emissions was only 1.7%.

Intensity of milk production affects feed production and the need of arable land. With less intensive milk production more forages can be fed. Because of the higher DM yield of grass compared with grain crops, more arable land is needed in intensive production systems compared to less intensive production. Regarding soil C sequestration, Vleeshouwers and Verhagen (2002) and Vellinga et al. (2004) assumed that growing grass would work as a sink for C, whereas other growing crops would cause a net release of C from soil. However, the values for both grass and other crops were highly variable. Soil organic carbon dynamics is often neglected in environmental assessments, mainly due to their high uncertainty (Cederberg et al. 2013). We estimated the difference in soil C sequestration required to offset the using DM yields of 6 000 and 3 500 kg DM ha^{-1} for grass and grain, respectively. The calculations were made using the data (milk yield 9 000 or 10 000 kg year^{-1} and beef production 80–90 million kg) from the present study. It was estimated that 98 kg ha^{-1} difference in soil C sequestration between grass and grain crops compensates for the greater CH_4 emissions in the less intensive system. Peat soils have high CO_2 emissions and the difference between grass and grain is much greater than in mineral soils; therefore, to minimize CO_2 losses from ruminant production peat soils should mainly be used for forage production. In Sweden, soil organic C stocks increased with the proportion of leys on the farm, and it was greater in dairy and beef farms compared with arable and pig farms (Henryson et al. 2022). It should also be noted that the effects of forage-based systems on the soil C stock are more permanent than the effects of increased milk production on CH_4 that is biogenic recyclable C (Liu et al. 2021).

Conclusions

Contrary to our hypothesis, increased milk production intensity decreased total CH_4 production at each targeted beef production level. However, even small differences in soil C sequestration between grass and grain production would compensate for the lower CH_4 emissions from intensive systems. In addition, at the lower levels of beef production than currently total manure N output decreased with increased intensity of milk production but at current or higher beef production levels the effects of milk yield were small. Based on the results, the current Finnish strategy of producing the targeted amount of milk and beef with high milk production intensity, relatively high slaughter weights and a reasonably low number of suckler cows seems to be effective in terms of CH_4 production and N emissions.

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