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Effects of herd management decisions on dairy cow longevity, farm profitability, and emissions of enteric methane – a simulation study of milk and beef production

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ABSTRACT

Sustainable dairy and beef production provides environmental, economic, and social values that can potentially be maximized by optimizing herd management strategies. The length of a dairy cow's life is affected by, and affects, all three pillars of sustainability. Longevity in dairy cows is multifactorial and strongly dependent on herd management. Despite genetic improvements, the average time of culling for Swedish cows has barely changed and is currently at 2.6 lactations. This culling rate requires a high number of replacement heifers, generating high rearing costs for farmers. This study evaluated different herd management strategies to improve cow longevity and assessed the effects on enteric methane (**CH_4**) emissions from the herd and the profitability of milk production and beef production from the dairy cows and their offspring. The base scenario, an average Swedish Holstein herd of 100 cows, was compared with seven scenarios simulated using a stochastic herd simulation model (SimHerd). Two of these scenarios involved improved health and survival of cows in the herd, three involved improved reproduction, one considered the consequences of keeping all surplus heifers in the herd, and one considered maximizing the use of X-sorted dairy semen and inseminating the rest of the herd with unsorted beef semen, to avoid surplus replacement heifers. Improved fertility had the greatest effect in increasing the productive life per cow, to 3.8 years compared with 2.8 in the base scenario, allowed for more use of beef semen, reduced the number of replacement heifers, and generated the highest herd profit (€98 per cow-year higher than base scenario). Keeping all surplus heifers instead of producing beef × dairy cross calves decreased the number of productive years by 0.8 and reduced profit by €22 per cow-year. The profit was highly associated with costs related to replacement heifers. The highest beef output (3 369 kg per year more than base scenario) was achieved by keeping all heifers and culling a high share of dairy cows, but this scenario also generated much higher enteric CH_4 emissions (+1 257 kg per year). Improving health, survival, or fertility reduced enteric CH_4 emissions by 90–255 kg per year, while total yearly beef production ranged from 59 kg less to 556 kg more than in the base scenario. Reducing the number of replacement heifers needed by improving cow reproductive performance is thus key to increasing cow longevity and profitability, while reducing enteric CH_4 emissions from the herd without compromising milk and meat production.

Implications

Sustainable dairy and beef production provides environmental, economic, and social values, but these values are affected by cow longevity. The key to extending cow longevity in dairy herds is to improve reproductive management and cow performance. This reduces the number of replacement heifers needed, which in turn increases herd profitability and reduces the climate impact of production. The need for fewer replacement heifers also offers an opportunity to increase the volume and value of beef produced by dairy cows, by using semen from beef breeds.

Introduction

Demand relating to dairy and beef products is shifting from more products towards more sustainable products (Alonso et al., 2020), and sustainable dairy and beef production brings environ-

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mental, economic, and social values. Environmental sustainability in terms of reducing greenhouse gas (**GHG**) emissions can potentially be improved by optimizing herd management (Knapp et al., 2014). Social sustainability includes animal welfare, which is of increasing importance to consumers of dairy products (de Graaf et al., 2016). Higher animal welfare is associated with increased cow longevity, i.e., cow lifetime (Langford and Stott, 2012), which reduces environmental impact, and improves herd profits (Grandl et al., 2019). The challenge for farmers is to produce enough beef and dairy products with lower GHG emissions while maintaining herd profitability.

Longevity in dairy cows is multifactorial and strongly dependent on herd management. Despite genetic improvements especially health and reproduction traits, the average age of cows at culling has not increased substantially in recent decades. The optimal culling rate differs between an economic and environmental perspective. For example, De Vries (2020) reported an economic optimum of five lactations per cow, while von Soosten et al. (2020) estimated that GHG emissions could be reduced by 25–43% if cows go through two to eight lactations compared with culling after one lactation. In Sweden, cows currently go through on an average of 2.6 lactations before culling (Växa Sverige, 2021). This could mean that improving cow longevity in Sweden has an economic and environmental potential.

There are ways to improve longevity in dairy cattle, e.g., through improved herd management (Alvåsen et al., 2018; Lehmann et al., 2019) and breeding (Stefani et al., 2018; Pritchard et al., 2013). The most common reasons for (involuntary) culling of Swedish dairy cattle are poor fertility and poor udder health (Växa Sverige, 2021; Ahlman et al., 2011), factors known to be associated with longevity (De Vries, 2020), so improving these factors is likely to increase cow longevity. Another main reason for (voluntary) culling cows is low production (Växa Sverige, 2021), which is often associated with an excess of replacement heifers with a higher genetic potential that enters the herd (De Vries, 2020). Swedish farmers may not be aware of the economic potential of reducing the surplus of replacement heifers, which partly explains the current average age of Swedish dairy cows.

Greater cow longevity means that cows are kept in the herd for longer, reducing the need for replacement heifers. This decreases the costs of raising heifers and provides the opportunity to use more beef semen in dairy cattle, potentially increasing the value and volume of beef produced by the dairy herd. When estimating GHG emissions from dairy herds, the impact from slaughter calves sold to beef producers is often disregarded. From an environmental point of view, moving beef production from suckler herds to dairy herds would reduce GHG emissions from the entire cattle sector, due to the allocation of total emissions to both milk and meat (Knapp et al., 2014). The decisions made on dairy farms can therefore influence the conditions for beef producers and total GHG emissions from the cattle sector, so it is important to consider joint production of beef and dairy, as done in this study.

The European ambition of becoming climate neutral by 2050 puts high pressure on the agricultural sector on reducing the climate impact. In 2023, one of the largest dairy companies in Europe introduces an incentive model to encourage their farmers to reduce their climate impact in turn for a higher milk price (Arla, 2022). Cow mortality is one of the factors in their incentive model. Other factors, such as feed efficiency measured as the feed use of all animals in the herd over produced milk, can be improved indirectly by reducing the number of young stock in the herd.

The aim of the study was to compare different herd management procedures for improving cow longevity in terms of the impact on enteric methane (**CH_4**) emissions and the profitability of combined dairy and beef production from dairy herds. Thus, the analysis included dairy cows, replacement heifers, and calves reared for beef production. Earlier work has shown the effects of system-changes or changes in efficiency (see e.g. Flysjö et al., 2011; Puillet et al., 2014; Faverdin et al., 2022). The novelty of this study is the simulated changes in management within a system that result in clear differences in the output on herd level.

Material and methods

Simulation model

The SimHerd model was used to simulate the effects of changes in dairy herd management at herd level. This Monte Carlo simulation model is heavily research-based since the early 1990s and has been employed in previous studies on various aspects of management changes (e.g., Østergaard et al., 2000; Lehmann et al., 2019; Clasen et al., 2020). SimHerd uses stochastic modeling of state changes at animal and herd level to simulate the effects of specified changes in biology and management. At weekly intervals, the age, lactation stage, milk yield (actual and potential), BW, stage in estrus cycle, state in parity, somatic cell count, disease status, and culling status are determined for each animal in the herd. The state of an animal may be altered by discrete events triggered by relevant probabilities, such as disease risk, heat detection, abortion, conception, death, and culling. The model works dynamically, such that for example the occurrence of a given disease may increase the risk of other diseases and reduce milk yield, growth, feed intake, and ability to express heat or become pregnant (Østergaard et al., 2005). Furthermore, the state of the animal also adds to the risk of developing a disease, the level of production etc. The state of all the animals in the herd defines the state of the herd, including herd demographics (Østergaard et al., 2010). Input parameters serve as decision variables to control herd dynamics, baseline risks of diseases, heat observation rate, culling strategy, production level, fertility, and health for the simulated herd. The simulation output consists of technical data on the herd that can be used in economic and other calculations, such as CH_4 output from the herd. In the present study, male calves and beef × dairy (**B** × **D**) calves were not simulated with SimHerd, but were treated as a model output, from which rearing costs, enteric CH_4 emissions, and beef output were calculated. Furthermore, the SimHerd model does not calculate optimal solutions, but is simply simulating the dynamics in a dairy herd based on the input that is provided.

SimHerd is not programmed for genetic improvement, and therefore, breeding values and genetic changes were not included in the simulations. Instead, the traits of each animal were sampled randomly based on the herd's phenotypic mean, which was derived from the input parameters specified in the base scenario plus one SD. Therefore, the phenotypic level of the animals did not change due to genetic improvement, but only due to changes in herd management. However, the economic, biological, and practical aspects of using different breeding strategies and reproduction technologies by the farmer are handled in the model.

Base herd scenario and input parameters

The base scenario (**BASE**) assumed was an average dairy herd in Sweden with Swedish Holstein cows in a conventional production system. The input parameters for milk yield, disease risks, reproduction, and culling were calibrated so that the results of this scenario reflected annual statistics (Supplementary Table S1, Växa Sverige, 2019; 2021) from the Swedish official milk recording scheme (managed by Växa Sverige, Uppsala, Sweden).

The average simulated herd size was 100 cows. A calving-ready heifer was assumed to replace a cow that died or was culled due to disease, poor fertility, or low milk production. If there was no available place for a calving-ready replacement heifer, it was sold as a pregnant heifer. If there were no replacement heifers available, the simulated herd purchased a pregnant heifer from a "fictive" herd. However, in the base herd, we sought to maintain a limited surplus (1–3) of heifers, to avoid buying in animals and to limit the number of pregnant heifers sold from the herd.

Cows culled due to disease were culled immediately. Each type of disease was associated with a certain risk of culling. Cows were added to the culling list if they had lower daily milk yield than the average of the herd at the certain stage of lactation or were unable to become pregnant within a specific timeframe between the voluntary waiting period and the maximum number of days open. Cows were inseminated at 49 days postcalving at the earliest, and at 299 days postcalving (first-parity cows) or 324 days (older cows) at the latest. Cows on the culling list due to low milk yield were withdrawn in case they became pregnant within the specified timeframe. Cows on the culling list remained in the herd until a calving-ready heifer was available to replace it. Heifers were sold if there were no cows on the culling list at the time, it was ready to enter the herd. Heifers were culled if they were unable to become pregnant between 470 and 810 days of age. The timeframes were calibrated to reach an average age at first calving of approximately 27 months and a calving interval of approximately 400 days, given the probabilities of heat detection and conception. All cows were dried off 8 weeks prior to calving, thus the length of lactation would be a result of a calving interval minus 56 days.

The herd input parameter for the probability of observed heat, defined as the animal's ability to show heat and the farmer's ability to detect heat, was 45% for cows and 65% for heifers. The probability of conception was 40% for cows and 62.5% for heifers. To maintain a limited surplus of heifers, 25% of the cows were inseminated with beef semen, while the other females in the herd were inseminated with conventional dairy semen. Because SimHerd does not simulate genetic progress, the selection of cows for beef semen was random. The conception rate was the same regardless of semen type. Insemination using either semen type had a 48% probability of resulting in a female calf. There was a 20% higher risk of stillbirth if the calf was male compared with female and a 5% higher risk if the calf was sired by a beef breed. Thus, a B × D bull calf had a 25% higher risk of stillbirth than a female dairy calf.

SimHerd outputs the numbers of liveborn dairy males and B × D calves but does not simulate the animals as with dairy females. In this study, we wanted to include the dairy males and B × D animals in the herd and therefore, we assumed they were reared until slaughter. We assumed the same young stock mortality as for dairy heifers.

Additional scenarios

Seven herd scenarios with management strategies that differed from the base herd were created. Two scenarios involved improvements in the health and survival of cows in the herd. In one of these (**HEALTH**), the risk of all diseases was half that in the BASE scenario, which in Sweden is already low (0.29 veterinary treatments per cow/year), and the use of beef semen was the same as in BASE. In the second (**SURVIVAL**), the mortality rate was halved. As a result, 30% of the cows were inseminated with beef semen to limit the surplus of replacement heifers.

Improvement of reproduction was investigated in three scenarios. In one (**HEAT)**, the probability of observing heat in cows was increased from 45 to 55%. In the second (**PREGNANCY)**, the probability of conception in cows was increased from 40 to 50%. The probabilities of heat detection and conception correspond to an increase from average practice to the top 25% level in Swedish herds. In the third (**FERTILITY)**, the probability of both heat detection and conception were increased as in HEAT and PREGNANCY. Improvement of fertility resulted in 45% inseminations with beef semen in cows for HEAT and PREGNANCY, and 55% inseminations in FERTILITY, to limit the surplus of replacement heifers.

The sixth scenario (**KEEP**) reflected the consequence of keeping all surplus heifers in the herd. If there was no cow on the culling list to be replaced with a heifer, a cow was voluntarily culled based on low milk yield. In this scenario, no beef semen was used.

The final scenario (**SEXED)** considered avoiding producing dairy bull calves and only producing dairy heifers and B × D crossbred calves. Thus, all heifers and 60% of first-parity cows were inseminated with X-sorted dairy semen and the rest of the herd with unsorted beef semen, to limit the surplus of replacement heifers. The probability obtaining of a female calf from using X-sorted semen was 90%, but at the expense of lower conception rate (85% of that for conventional semen).

The scenarios were simulated for 50 years, to ensure that equilibrium was reached, i.e., that herd dynamics were stable. However, in most scenarios, equilibrium was reached at approximately year 10 of the simulation. The results presented are yearly averages of 100 replicates over the last five years at equilibrium. Because the simulations did not include genetic improvements, any variation between replicates represented stochastic error.

Beef production

The carcass weight of a cow at slaughter was assumed to be 50% of the live weight simulated based on the cow's age and body condition score. Dairy and B × D bull calves were assumed to be slaughtered at 18 months of age, with a carcass weight at 340 kg and 395 kg, respectively. Beef × dairy cross heifers were assumed to be slaughtered at 24 months of age, with a carcass weight of 315 kg (Jamieson, 2010). A continental beef breed (e.g., Charolais or Simmental) was assumed for the sires of B × D calves.

Methane output

Enteric CH_4 emissions from the different animal categories were calculated using the NorFor model (Nielsen et al., 2013). For dairy cows, the calculations were based on hypothetical DM intake and feed fatty acids. Model adjustments made in SimHerd according to Kristensen and Lund (2012) and in dialog with the NorFor group were applied. For dairy heifers, dairy bulls, and B × D calves, equations including hypothetical dietary proportions of concentrate according to Bertilsson (2016) were used. Enteric CH_4 emissions from dairy cows were allocated between milk and meat according to IDF (2015), by approximately 85% on milk and 15% on meat. Emissions from the calves that were born and reared for beef meat were accounted for as emissions on meat only.

Estimated enteric CH_4 emissions per kg milk (or ECM) included emissions from dairy cows and replacement heifers, while estimated enteric CH_4 emissions per kg beef meat (including bone) were calculated as the product of meat mass from each animal category and its per-kg emissions.

Price and feed assumptions

The feed intake was dynamically simulated for each animal according to the level of milk production, BW gain, requirement for a growing fetus, and health status (Østergaard et al., 2005). Cows were assumed to be fed a total mixed ration (60% of DM as roughage) and each cow consumed on average 1.5 kg DM per kg ECM produced during the lactation period. Each heifer consumed on average 1 950 kg DM per year. All bull calves were assumed to eat 20% more than heifers (dairy and B × D).

The economic estimates included income from milk production, beef production, and surplus replacement heifers, and the costs of insemination (including the service fee), disease treatments, and other costs (e.g., bedding, hoof trimming, vaccinations, etc.). Essential price assumptions are listed in Table 1. Labor costs were included for replacement heifers and calves reared for slaughter, with the labor cost for slaughter calves assumed to be 50% lower than for replacement heifers. Labor costs for cows and costs associated with buildings, farming equipment, and other investments were not included, because they were assumed to be constant across the scenarios. Other costs related to calves reared for slaughter were assumed to be 30% lower for B × D heifers and 50% lower for male calves than for replacement heifers. All assumptions for costs associated with dairy bull calves and B × D calves relative to replacement heifers were based on contribution margin calculations for a Swedish province (Länsstyrelsen Västra Götaland, 2019).

Sensitivity analysis on carcass value

The economic consequence of changes in carcass values for cull cows and dairy bull calves and B × D calves were investigated using the same herd scenarios as in the original simulations, but with the carcass value for cows, dairy bull calves, and B × D crossbred calves altered by −50, −25, +25, and +50% from the default prices (Table 1), while keeping all other prices constant. The profit from each scenario on changing only carcass value for cows, only for dairy bull calves and B × D calves, or for both was compared against that in BASE.

Results

Technical results

Improving both heat observation and conception rate (FERTILITY) had the largest effect in increasing the productive life per cow (3.8 years, compared with 2.8 in BASE) (Table 2). Decreasing cow mortality or improving single fertility traits also increased the number of productive years (3.1–3.4). Improving health traits only increased the number of productive years by 0.1. Keeping all surplus heifers instead of producing B × D calves (KEEP) and avoiding dairy bulls by using sexed semen (SEXED) decreased the number of productive years by 0.8 and 0.1, respectively.

Reducing the number of replacement heifers, especially from improving fertility traits in FERTILITY, allowed for more use of beef semen, which increased the number of B × D calves born and slaughtered each year. Increasing the productive life and reducing the replacement rate in the herd resulted in slightly more disease treatments; however, because of a higher proportion of third parity and older cows with a potentially higher risk of becoming ill. Moreover, despite shorter cow productive life, there were more disease treatments in KEEP because of more calvings per year.

The calving interval was 5–12 days shorter in HEAT, PREGNANCY, FERTILITY, and KEEP than in BASE (401 days) (Table 2). Improving cow fertility traits shortened the calving interval, as an effect of higher reproduction efficiency. In KEEP, the calving interval was shorter on average because cows were more likely to be culled earlier if a replacement heifer was ready to enter the herd. The age at first calving was between 26.7 and 27 months of age across the scenarios (data not shown in table).

The milk yield remained relatively unchanged in all scenarios except KEEP, where ECM yield was 192–275 kg higher per cow-year than in the other scenarios (Table 2). The proportion of dry cows throughout the year was 10% across all scenarios, except for in FERTILITY and KEEP, where it was 11 and 9%, respectively (data not shown in table).

The simulated carcass weight of culled cows ranged between 307 and 318 kg, with the heaviest in FERTILITY and the lightest in KEEP due to the average age of cows in the herd in those scenarios. However, because of the low replacement rate in FERTILITY, the meat output from culled cows was only 6 313 kg, compared with 13 198 kg in KEEP, which had the highest replacement rate (Table 3). Despite zero meat production from B × D calves, total meat production was highest in KEEP (31 026 kg) and lowest in HEALTH (27 598 kg) and BASE (27 657 kg).

There were only marginal differences between the scenarios in terms of stillbirth and calf mortality (data not shown), due to the stochasticity of the simulation model. The stillbirth rate ranged between 8.6 and 8.8% and calf mortality between 3.4 and 3.8%.

Economic results

On combining income and costs associated with dairy production and offspring for beef production, the total profit per cow-year was highest in FERTILITY, €98 higher than in BASE (Table 4). The scenarios KEEP and SEXED resulted in a loss of €22 and €6 per cow-year compared with BASE. In the remaining scenarios, the profit per cow-year was between €24 and €60 higher than in BASE.

Because of higher meat output from culled cows and higher milk production, the total income from both meat and milk was highest in KEEP, although this scenario was also associated with higher costs due to higher replacement rate (Table 4). Around 30% of the total costs of milk production were associated with replacement heifers in KEEP, but only 19% in FERTILITY. However, the costs associated with raising dairy bull calves and B × D calves were highest for FERTILITY. Costs for insemination were highest for SEXED, because of the relatively higher cost of sexed semen, which was only used in this scenario.

The cost of raising a replacement heifer was on average €1 351, assuming a calving age of 26.7 months. The cost of raising a B × D heifer to slaughter at 24 months of age was €889, while the cost of raising a dairy or B × D bull to slaughter at 18 months of age was €731.

Methane emissions

Keeping all heifers for replacement, as in the KEEP scenario, resulted in the highest annual emissions of enteric CH_4 from the entire herd, including the calves reared for slaughter (Table 5). The main reason for this was the length of the rearing period. The replacement heifers contributed to CH_4 emissions until their

Table 1
Price assumptions used in the simulations of the dairy cattle herd.

Item	Price, €
Milk, per 1 000 kg ECM[1]	372
Slaughter cow, per kg carcass	2.625
Dairy bull, 18 months, 340 kg carcass	1 020
Beef × dairy bull, 18 months, 395 kg carcass	1 274
Beef × dairy heifer, 24 months, 315 kg carcass	1 008
TMR[2], cows, per kg DM	0.19
Concentrate, young stock[3], per kg DM	0.27
Roughage, young stock, per kg DM	0.18
Conventional semen (incl. service)	34
Sexed semen (incl. service)	39
Beef semen (incl. service)	34
Labor cost, per replacement heifer per year	261.6
Labor cost, per slaughter calf per year	130.8

[1] Energy-corrected milk.
[2] Total mixed ration.
[3] Feed costs were assumed to be 20% higher for dairy and beef × dairy bulls.

Table 2
Technical results of dairy production for a 100-cow herd per year in the eight scenarios.

Item	BASE	HEALTH	SURVIVAL	HEAT	PREGNANCY	FERTILITY	KEEP	SEXED
Productive years/cow	2.8	2.9	3.1	3.4	3.4	3.8	2.0	2.7
Replacement, %	35	35	33	30	29	26	49	38
ECM[1]/cow-year	10 047	10 061	10 078	10 014	10 023	10 033	10 289	10 097
Proportion of ≥3rd lactation cows	0.44	0.45	0.47	0.50	0.51	0.56	0.37	0.44
Replacement heifers/year	81	81	77	66	65	57	109	89
Dairy bull calves/year	59	59	55	47	47	41	79	7
Beef × dairy heifers/year	15	15	18	28	28	36	0	47
Beef × dairy calves/year	12	12	14	22	22	29	0	38
Calvings/cow/year	1.03	1.03	1.02	1.01	1.02	1.03	1.16	1.06
Replacement heifers born/year	38	38	36	31	31	27	51	41
Dairy bull calves born/year	41	40	38	32	33	29	55	5
Beef × dairy heifers born/year	7	8	9	14	14	19	0	24
Beef × dairy bull calves born/year	8	8	10	15	15	20	0	26
Calving interval, d	401	401	401	396	395	389	394	401
Reproduction efficiency (cows)	0.18	0.18	0.18	0.22	0.23	0.27	0.18	0.18
Disease treatments/cow-year	0.29	0.20	0.30	0.31	0.30	0.32	0.30	0.30
Cow mortality, %	6.3	6.2	3.1	6.4	6.3	6.3	6.3	6.5

[1] Energy-corrected milk.

Table 3
Meat output in kg carcass for a 100-cow herd per year for culled cows, dairy bull calves, beef × dairy (B × D) heifers and bulls in the eight scenarios.

Category	BASE	HEALTH	SURVIVAL	HEAT	PREGNANCY	FERTILITY	KEEP	SEXED
Culled cows	9 060	9 028	9 299	7 314	7 326	6 313	13 198	9 692
Dairy bull calves	13 210	13 210	12 372	10 656	10 706	9 477	17 828	1 538
Beef × dairy heifers	2 264	2 291	2 785	4 341	4 341	5 672	0	7 274
Beef × dairy bull calves	3 023	3 069	3 671	5 800	5 840	7 615	0	9 930
Total	27 657	27 598	28 127	28 112	28 213	29 077	31 026	28 434

Table 4
Economic outcome for a 100-cow herd (€ per cow-year) of beef and dairy production in the eight scenarios.

Item	BASE	HEALTH	SURVIVAL	HEAT	PREGNANCY	FERTILITY	KEEP	SEXED
INCOME								
Milk	3 716	3 728	3 724	3 699	3 703	3 704	3 815	3 736
Meat – culled cows	238	237	244	192	192	166	346	254
Meat – calves	569	569	579	646	648	711	535	599
Surplus heifers	19	22	24	11	10	9	–	31
Sum	4 542	4 556	4 571	4 548	4 553	4 590	4 696	4 620
COSTS – DAIRY								
Feed – cows	1 249	1 250	1 251	1 245	1 246	1 247	1 272	1 253
Feed – heifers	224	224	212	182	180	157	302	247
Disease treatments (cows)	27	18	28	30	29	30	29	28
Inseminations	48	47	47	47	40	41	55	59
Other (cows)	144	144	140	144	144	144	144	144
Other (heifers)	50	50	47	41	40	35	67	55
Labor (heifers)	212	211	200	173	170	149	285	234
Sum	1 954	1 944	1 925	1 862	1 849	1 803	2 154	2 020
COSTS – BEEF								
Feed	273	273	278	306	308	336	261	277
Other	28	28	29	33	33	37	24	34
Labor	111	111	113	127	127	140	103	119
Sum	412	412	420	466	468	513	388	430
PROFIT/cow-year	2 176	2 200	2 226	2 220	2 236	2 274	2 154	2 170
Difference from BASE		+24	+50	+44	+60	+98	−22	−6

first calving at 26.7–27 months of age, while the lifetime of bulls was 18 months and that of B × D heifers was 24 months. At herd level, the differences from the BASE scenario were most evident (reduction of 90–255 kg CH_4 per year) in the scenarios where cow mortality (SURVIVAL) and fertility (HEAT, PREGNANCY, FERTILITY) were improved, and thus, the number of replacement heifers was reduced. Compared with BASE, emissions increased by 1,257 kg CH_4 in KEEP, where no beef semen was used, and by 862 kg CH_4 in SEXED, where beef semen was used to a large extent. The latter resulted in a large share of B × D heifers that were slaughtered at 24 months (beef semen was not sexed in any scenario), but few dairy bulls were born and reared for beef. Considering only the share of enteric CH_4 emissions produced from replacement heifers in relation to dairy cows, the heifers contributed between 14 and 24% of the total, with the lowest contribution in FERTILITY and the highest in the KEEP scenario.

When enteric CH_4 emissions were calculated per kg ECM, there were only small differences between the scenarios (Table 6). The scenarios SURVIVAL, PREGNANCY, and FERTILITY reduced the emissions intensity most compared with BASE (by 0.3–0.4 g CH_4/kg ECM), while SEXED gave the largest emissions (an extra 0.3 g CH_4/kg ECM). This was an effect of the number of replacement hei-

Table 5
Total enteric methane emissions (kg) for a 100-cow herd per year from each category of animal and for the total herd in the eight scenarios without allocation on beef or milk production.

Category	BASE	HEALTH	SURVIVAL	HEAT	PREGNANCY	FERTILITY	KEEP	SEXED
Dairy cows	15 293	15 312	15 316	15 251	15 260	15 269	15 577	15 347
Replacement heifers	3 667	3 661	3 467	2 988	2 940	2 573	4 940	4 048
Dairy bull calves	2 107	2 092	1 962	1 675	1 683	1 481	2 826	244
Beef × dairy heifers	607	614	748	1 155	1 156	1 501	0	1 953
Beef × dairy bull calves	412	418	501	785	790	1 024	0	1 356
Total	22 085	22 097	21 995	21 853	21 830	21 847	23 343	22 948
Difference from BASE		12	−90	−232	−255	−238	1 257	862

Annual methane emissions from the different animal categories were (in kg/year): Dairy cow (153), replacement heifer (45), dairy bull calf (36), beef × dairy bull calf (36), beef × dairy heifer (42). Total emissions during the rearing period are re-calculated to emissions per year for the growing animals (Kristensen and Lund, 2012; Nielsen et al., 2013; Bertilsson, 2016).

fers in combination with the allocation between milk and meat. For KEEP, emissions were 0.1 g CH_4/kg ECM lower than in BASE, because of the relatively higher milk yield.

KEEP and SEXED generated the largest CH_4 emissions from meat production (6 and 11 kg CH_4 more than in BASE), while FERTILITY generated the lowest (6 kg CH_4 less than in BASE). Depending on the total volume of milk and meat produced in the herd, AF ranged from 0.81 to 0.89 in the different scenarios, with the highest value in FERTILITY and the lowest in KEEP.

Sensitivity analysis on carcass values

The effect of changing the carcass value of culled cows on yearly profits per cow depended on the number of cows culled compared with BASE (Table 7). Because everything else was kept stable, the tendencies are linear. Scenarios culling more cows than BASE benefited from higher cull cow values, while scenarios culling fewer cows were penalized by lower cull cow values. The most sensitive scenario was KEEP, where the difference from BASE at the default carcass price (−€22) declined by €54 at 50% lower price and increased by €55 at 50% higher price. Thus at default and with decreasing value of cull cow carcasses, the yearly profit per cow was lower than in BASE, while at higher carcass values, it exceeded that in BASE. Because the number of culled cows was similar, the difference between HEALTH (the least sensitive scenario) and BASE scarcely changed at 50% higher and lower carcass prices.

The effect of changing the carcass value of dairy bull calves and B × D calves on yearly profits per cow depended on the relative number of calves slaughtered compared with BASE, but also on the category of calves (dairy bulls or B × D) (Table 7). The FERTILITY scenario slaughtered most calves and was therefore most sensitive, with the profit per cow-year relative to BASE decreasing/increasing by €71 from the default value at 50% lower/higher slaughter calf carcass values. Despite relatively more B × D calves (i.e., more valuable calves) being sold in SEXED compared with FERTILITY, the profit per cow-year only decreased/increased by €15 from the default value at 50% lower/higher slaughter calf carcass values. Even though SURVIVAL slaughtered 86 more calves than SEXED, the sensitivity of SURVIVAL to a change in calf carcass value was lower (€3 decrease/increase compared with BASE at 50% lower/higher prices).

The effect of changing carcass values for both culled cows and dairy bull calves and B × D calves was highest for FERTILITY and KEEP. In FERTILITY, the profit per cow-year changed by €35 from default at 50% higher or lower carcass values, but even at 50% lower carcass values the profit in FERTILITY was still €63 higher than in BASE. For KEEP, the profit relative to default changed by €37, but only exceeded that in BASE (+€14) at 50% lower prices. For SEXED, the profit exceeded that in BASE (+€5) at 25% higher carcass values. Hence, in these simulations, the breakeven carcass value was somewhere between 25 and 50% higher than the default for KEEP, and between 0 and 25% higher than the default for SEXED.

Regardless of changes in cull cow values, slaughter calf values, or both, the profit per cow-year in SURVIVAL changed relatively little compared with BASE (Table 7). At 50% lower carcass value for dairy bull calves and B × D calves, SURVIVAL became the most profitable scenario.

Discussion

This study revealed differences in economic returns for scenarios with high and low dairy cow replacement rate due to management changes, mostly driven by differences in factors other than milk yield. Overall, the results indicated that improving cow reproduction can be an important prerequisite for reducing the replacement rate. Enteric CH_4 emissions were lowest in alternatives with a low replacement rate, which also showed better economic performance.

Milk and meat production

Yearly milk (ECM) yield per cow was barely affected by increasing the number of productive years of the cow but increased by more than 100 kg per cow-year in a scenario (KEEP) where the number of productive years was decreased by almost a year. Higher lactation numbers are associated with higher milk yield, but in a 365-day herd perspective, the milk yield per cow (or slot in the barn) tends to decrease when the average age of the cows increases. Because of the pressure from heifers calving and entering the production herd, more cows were culled due to low milk production and there were more calvings within a year in KEEP compared with the other scenarios. Hence, there were more high-yielding cows, more first parity cows, and more cows were at the peak of their lactation within a year, thus affecting the milk yield. In the other scenarios, where the number of productive years

Table 6
Estimated enteric methane emissions (g per kg) energy-corrected milk (ECM) for a 100-cow herd, including emissions from dairy cows and replacement heifers and for all beef meat produced (g per kg carcass weight) as the sum of emissions from different animal categories in the eight scenarios.

Category	BASE	HEALTH	SURVIVAL	HEAT	PREGNANCY	FERTILITY	KEEP	SEXED
ECM	16.3	16.3	16.0	16.1	16.0	15.9	16.2	16.6
Beef meat	208	208	208	205	204	202	214	219

Table 7
Change in income (€ per cow-year) from culled cows and dairy bull calves and B × D (beef × dairy) calves and total profit per cow-year compared with the base scenario, when changing the slaughter price by 25 and 50% below and above the default simulation price.

Item	HEALTH	SURVIVAL	HEAT	PREGNANCY	FERTILITY	KEEP	SEXED
Profit/cow-year on changing cull cow carcass value							
−50%	23	47	66	83	134	−76	−14
−25%	23	48	55	72	116	−49	−10
Default	23	50	44	60	98	−22	−6
+25%	23	52	32	49	80	5	2
+50%	22	53	21	37	62	33	2
Profit/cow-year on changing slaughter calf carcass value							
−50%	24	45	5	21	27	−5	−21
−25%	24	48	24	40	62	−13	−14
Default	24	50	44	60	98	−22	−6
+25%	23	52	63	80	133	−30	1
+50%	23	55	82	100	169	−39	9
Profit/cow-year on changing both cull cow and slaughter calf carcass values							
−50%	24	42	28	43	63	−59	−29
−25%	24	46	36	52	80	−40	−18
Default	24	50	44	60	98	−22	−6
+25%	23	54	51	69	115	−3	5
+50%	23	58	59	77	133	15	17

increased, there were more lower-yielding cows, fewer calvings than in KEEP, hence more older cows, and more cows in mid- or late lactation.

A presumed dilemma with meat production from the dairy sector is that an increase in milk production per dairy cow would reduce meat production because there are fewer dairy cows to generate the same amount of milk. Thus, to maintain the overall quantity of meat produced, it would be necessary to produce more meat from suckler cow systems, which have lower production efficiency, thus increasing the climate impact (Vellinga and de Vries, 2018). A promising solution could be to use sexed semen and B × D crosses, as shown in the present study.

Unsorted beef semen was assumed in simulations in this study. Using Y-sorted sexed beef semen to increase the probability of B × D male calves could generate higher beef output per year. From an economic point of view, producing B × D bulls instead of B × D heifers would thus be more profitable. However, this may only apply when economic calculations are based on the whole dairy enterprise, i.e., considering both milk and beef production, as done in this study. In a study by Ettema et al. (2017) that only considered the dairy farm and assumed that calves for slaughter were sold at two weeks of age, using Y-sorted sexed beef semen was not more profitable than using conventional beef semen unless the price of semen was the same in both cases. From an environmental point of view, producing B × D bulls could reduce GHG emissions from the enterprise compared with B × D heifers, due to the shorter rearing period for the bulls. However, rearing heifers on pasture has benefits for biodiversity compared with rearing bulls in confinement, so there is a trade-off between GHG emissions and enhancing biodiversity (de Vries et al., 2015; Torres-Miralles et al., 2022). Rearing bulls in confinement was the choice of this study since it is the most common production system for beef in Sweden today. If bulls were reared as steers, then grazing would be possible with the same benefits for biodiversity as with heifers. In addition, stillbirth and dystocia are expected to increase when most B × D calves born are bulls, but using beef breed bulls with genetic merit indices on B × D performance may solve or reduce this problem (Eriksson et al., 2020).

When calculating the economic returns from the slaughter of animals, we considered differences in carcass conformation but not meat quality, such as marbling, tenderness etc. At present, the major slaughterhouses in Sweden ignore meat quality and only pay based on EUROP carcass conformation score. The production system and length of the rearing period may affect meat quality and beef breeds and B × D calves are known to have more valuable carcass conformation, along with a higher growth rate (Pfuhl et al., 2007; Vestergaard et al., 2019), and are therefore more valuable as slaughter animals, so there is value in producing B × D calves instead of dairy bull calves for slaughter. Moreover, B × D bulls have higher carcass scores and growth rate than B × D heifers (Vestergaard et al., 2019), so producing only B × D bulls by using Y-sorted sexed beef semen could add value. Meat quality differs between breeds and can be measured in several ways. For example, dairy breeds tend to have better marbling scores and intramuscular fat than beef breeds (Pfuhl et al., 2007; Bown et al., 2016), while tenderness is similar or better for beef breeds (Pfuhl et al., 2007; Bureš and Bartoň, 2018). Thus, complementing those qualities when crossing dairy and beef breeds may have favorable effects on overall meat quality.

Methane emissions

Of the GHGs emitted from livestock production, only enteric CH_4 emissions were accounted for in the calculations in this study, since CH_4 is considered the most important GHG in the cattle sector (Gerber et al., 2013). Considering only direct enteric CH_4 emissions also allowed us to assess the impact of number of animals in the herd and differences in their life span. Differences were clearly visible in the amount of CH_4 emitted annually from the total herd, which was lowest in scenarios with increased fertility, and also in the intensity measure of CH_4 per kg of meat produced. The KEEP scenario, with the highest amount of meat produced, had the second highest emissions intensity due to the large number of replacement heifers. Only the SEXED scenario showed higher emissions intensity for the meat, due to a high number of heifers (both dairy and B × D) and a lower amount of meat produced. Nevertheless, the KEEP scenario had slightly lower emissions intensity than BASE when measured as per kg ECM, simply because the cows produced more milk and only replacement heifers and not dairy bull calves and B × D calves were included in the calculation of methane emissions per kg ECM. Therefore, emissions from cows, replacement heifers, and dairy bull calves and B × D calves should be included in emissions calculations. Increasing the productive life in the herd and thus keeping some cows with lower milk production (that may have been culled in scenarios with short life span) did not affect emissions intensity negatively in this study. First parity cows have approximately 15% lower yield per lactation than older cows (Växa Sverige, 2021). Even if the total emissions per cow increase with an increased life span, the emissions per unit of milk are reduced considering the rearing period and the length of the productive life (von Soosten et al., 2020).

Genetic benefits and opportunity costs

The genetic benefits of using X-sorted sexed semen and beef semen were not considered, which means that the true economic benefit of this may have been underestimated. Using beef semen in cows with the lowest genetic merit and sexed semen in cows or heifers with the highest genetic merit makes it possible to produce the next generation of replacement heifers from the best dams in the herd. In a previous simulation study that considered the genetic benefits of only using sexed and beef semen, Clasen et al. (2021) estimated that this added €11 per cow-year. On applying that value to the results in this study, the total profit in the SEXED scenario would be €5 higher than in BASE.

Generating a surplus of heifers using sexed semen may be economically beneficial if the market value of pregnant heifers exceeds the cost of raising heifers and the profit from B × D calves (Pahmeyer and Britz, 2020; Ettema et al., 2017). However, generating a surplus of replacement heifers will still reduce cow longevity and increase GHG emissions at sector level, as shown for the KEEP scenario. Moreover, we assumed a conception rate of 0.85 relative to conventional semen, which may be a conservative value according to recent studies reporting a conception rate of 0.90 (Bittante et al., 2020). Because the genetic gain was disregarded in SEXED, the effects on herd performance and dynamics were mostly affected by the lower conception rate for sexed semen, which led to slightly more culling than in BASE.

A common justification for high replacement rate is higher genetic level of replacement heifers (Bergeå et al., 2016; Alvåsen et al., 2018), an aspect that was not considered in the present study. De Vries (2020) quantified the genetic opportunity costs of lower replacement rates and found that these costs did not outweigh the benefits of lower replacement rates under US conditions. Genetic opportunity costs are the result of a larger genetic lag between the active bull population and the cows in the herd. Increased genetic lag due to extended lactations was studied by Clasen et al. (2019), who found a rather small effect on genetic returns if sexed semen was used strategically on heifers. Hence, with a strategic use of sexed semen, the difference in returns between alternatives' low versus high replacement rates can be expected to be only marginally smaller when genetic opportunity costs are considered.

Economic returns and sensitivity analysis

The sensitivity of total profit to carcass values was highest in scenarios that differed most from BASE in terms of numbers of culled cows and dairy bull calves and B × D calves (Table 7). Culling more cows in the KEEP scenario relative to BASE was only profitable at high culling values, although the yearly profit per cow never exceeded that in FERTILITY, where fewer cows were culled. Thus, culling healthy cows because of an excess of replacement heifers may be profitable at high cull values, but it is unlikely to be the best management strategy in terms of profit. Decreasing cow mortality in SURVIVAL proved the most economically safe scenario, because it maintained a relatively high and stable profit, compared with BASE, at changing carcass values. Sensitivity to other essential prices, such as feed and milk, was not investigated in this study, but is likely to be highest in scenarios keeping more young stock (Clasen et al., 2020).

Capacity costs were not included in the simulations in this study, and thus, the estimated profit for each scenario must pay those costs. Assuming fixed capacity in BASE, the scenarios SURVIVAL, HEAT, PREGNANCY, and FERTILITY did not utilize full capacity because the spots available from having fewer replacement heifers per year were not fully covered by a slaughter calf. This unfilled capacity could be used for increasing the herd size (or for finishing cull cows, as discussed earlier). However, increased production might even lead to greater emissions than in the base scenario. Dividing the number of spots in each scenario relative to BASE by the number of young stock (replacement heifers and dairy bull calves and B × D calves) reared per cow-year gave the opportunity for four additional cows in HEAT, PREGNANCY, and SURVIVAL, and two additional cows in SURVIVAL. In contrast, KEEP and SEXED would need to create 14 and 12 additional places, respectively, or reduce the number of cows in the herd to accommodate the capacity in BASE.

General considerations

Apart from FERTILITY, which combined the management changes made in HEAT and PREGNANCY, the scenarios simulated in this study only considered the effect of individual management changes. Combining the effects of e.g., HEALTH, SURVIVAL, and FERTILITY might have more favorable effects on cow longevity, herd profit, beef production, and methane emissions, or the combined effects may not be additive. Other possible management changes not simulated in this study were e.g., extended lactation and earlier calving age. It has been shown that reducing the age at first calving to 24 months reduces the non-milk producing period of the cow's life span and the number of replacement heifers, and therefore has a significant effect on enteric CH_4 emissions at herd level (Hristov et al., 2013; Knapp et al., 2014). The effect of extended lactation was not modeled in the present study but has been shown to have beneficial effects on lifetime productivity (milk yield) and GHG emissions, which are reduced mainly due to reduced number of replacement heifers and fewer dry cows (Lehmann et al., 2019; Sehested et al., 2019).

Based on the results in this study, there is an economic incentive to improve cow longevity in dairy herds and decrease enteric CH_4 emissions from dairy production. However, economic benefit is not the only factor motivating farmers to change or invest in new management strategies, e.g., farmers may be hesitant to adopt changes that are too time-consuming relative to the benefits (Wallin and Nordström Källström, 2019). Further, there are different ways of improving health, fertility, and cow mortality, and the magnitude of investment to make these improvements may differ between individual herds. For instance, improving cow fertility may be a matter of spending more man-hours checking for cows in heat or may involve investment in technological equipment. Improving health and cow mortality may simply require small management changes or staff training, or construction/refurbishment of buildings. Overall, the economic benefit of improving longevity would need to cover the costs generated.

Farmers may also be hesitant to take actions on reducing the climate impact from their production system if there is no noticeable effect for them (Barnes and Toma, 2012). Political actions, such as "CO_2 quotas", are not unlikely in the near future, and therefore farmers might soon be forced to reduce their climate impact. As mentioned earlier, the largest commercial dairy in Sweden and Denmark (Arla) has launched a new climate incentive system whereby dairy farmers can obtain a higher milk price. This study showed that focusing climate impact reduction efforts on reducing the number of young stock by improving cow health, survival, or reproductive efficiency can also be favorable for herd profitability, animal welfare, and dairy and beef production. Furthermore, reducing the number of young stock may also be beneficial in terms of reductions in nitrous oxide from manure management and feed production, although actions need to be evaluated for potential trade-offs or counteractions. Efforts to reduce greenhouse gas emissions from manure management may result in higher ammonia emissions and nitrate leakage in the field (Grossi et al., 2019).

In conclusion, we showed that reducing the number of replacement heifers, and thereby the replacement rate, is key to improving cow longevity and reducing enteric CH_4 emissions per kg ECM from dairy herds. A prerequisite for a substantial reduction in replacement rate is good reproductive performance in the existing herd, which also creates an economic benefit and does not compromise total milk and meat production from the herd.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2023.101051.

Ethics approval

This study was entirely a simulation study and did not involve live animal experimentation.

Data and model availability statement

None of the data were deposited in an official repository. Output data from the SimHerd simulation can be obtained by contacting the corresponding author.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence-assisted technologies in the writing process.

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Declaration of interest

None.

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References

Ahlman, T., Berglund, B., Rydhmer, L., Strandberg, E., 2011. Culling reasons in organic and conventional dairy herds and genotype by environment interaction for longevity. Journal of Dairy Science 94, 1568–1575. https://doi.org/10.3168/jds.2010-3483.

Alonso, M.E., Gonzalez-Montana, J.R., Lomillos, J.M., 2020. Consumers' concerns and perceptions of farm animal welfare. Animals (Basel) 10, 385. https://doi.org/10.3390/ani10030385.

Alvåsen, K., Dohoo, I., Roth, A., Emanuelson, U., 2018. Farm characteristics and management routines related to cow longevity: a survey among Swedish dairy farmers. Acta Veterinaria Scandinavica 60, 38. https://doi.org/10.1186/s13028-018-0390-8.

Arla, 2022. Arla earmarks up to 500 mEUR annually for rewarding climate activities on farm. Accessed Nov. 22, 2022. https://www.arla.com/company/news-and-press/2022/pressrelease/arla-earmarks-up-to-500-meur-annually-for-rewarding-climate-activities-on-farm/.

Barnes, A.P., Toma, L., 2012. A typology of dairy farmer perceptions towards climate change. Climatic Change 112, 507–522. https://doi.org/10.1007/s10584-011-0226-2.

Bergeå, H., Roth, A., Emanuelson, U., Agenäs, S., 2016. Farmer awareness of cow longevity and implications for decision-making at farm level. Acta Agriculturae Scandinavica, Section A—Animal Science 66, 25–34.

Bertilsson, J., 2016. Updating Swedish emission factors for cattle to be used for calculations of greenhouse gases Report no. 292. Department of Animal Nutrition and Management. Swedish University of Agricultural Sciences, Uppsala, Sweden.

Bittante, G., Negrini, R., Bergamaschi, M., Cecchinato, A., Toledo-Alvarado, H., 2020. Pure-breeding with sexed semen and crossbreeding with semen of double-muscled sires to improve beef production from dairy herds: Factors affecting heifer and cow fertility and the sex ratio. Journal of Dairy Science 103, 5246–5257. https://doi.org/10.3168/jds.2019-17932.

Bown, M.D., Muir, P.D., Thomson, B.C., 2016. Dairy and beef breed effects on beef yield, beef quality and profitability: a review. New Zealand Journal of Agricultural Research 59, 174–184. https://doi.org/10.1080/00288233.2016.1144621.

Bureš, D., Bartoň, L., 2018. Performance, carcass traits and meat quality of Aberdeen Angus, Gascon, Holstein and Fleckvieh finishing bulls. Livestock Science 214, 231–237.

Clasen, J.B., Lehmann, J.O., Thomasen, J.R., Ostergaard, S., Kargo, M., 2019. Combining extended lactation with sexed semen in a dairy cattle herd: Effect on genetic and total economic return. Livestock Science 223, 176–183. https://doi.org/10.1016/j.livsci.2019.03.001.

Clasen, J.B., Fikse, W.F., Kargo, M., Rydhmer, L., Strandberg, E., Ostergaard, S., 2020. Economic consequences of dairy crossbreeding in conventional and organic herds in Sweden. Journal of Dairy Science 103, 514–528. https://doi.org/10.3168/jds.2019-16958.

Clasen, J.B., Kargo, M., Ostergaard, S., Fikse, W.F., Rydhmer, L., Strandberg, E., 2021. Genetic consequences of terminal crossbreeding, genomic test, sexed semen, and beef semen in dairy herds. Journal of Dairy Science 104, 8062–8075. https://doi.org/10.3168/jds.2020-20028.

de Graaf, S., Van Loo, E.J., Bijttebier, J., Vanhonacker, F., Lauwers, L., Tuyttens, F.A.M., Verbeke, W., 2016. Determinants of consumer intention to purchase animal-friendly milk. Journal of Dairy Science 99, 8304–8313. https://doi.org/10.3168/jds.2016-10886.

De Vries, A., 2020. Symposium review: Why revisit dairy cattle productive lifespan? Journal of Dairy Science 103, 3838–3845. https://doi.org/10.3168/jds.2019-17361.

De Vries, M., Van Middelaar, C., De Boer, I., 2015. Comparing environmental impacts of beef production systems: A review of life cycle assessments. Livestock Science 178, 279–288.

Eriksson, S., Ask-Gullstrand, P., Fikse, W.F., Jonsson, E., Eriksson, J.A., Stalhammar, H., Wallenbeck, A., Hessle, A., 2020. Different beef breed sires used for crossbreeding with Swedish dairy cows - effects on calving performance and carcass traits. Livestock Science 232,. https://doi.org/10.1016/j.livsci.2019.103902 103902.

Ettema, J.F., Thomasen, J.R., Hjorto, L., Kargo, M., Ostergaard, S., Sorensen, A.C., 2017. Economic opportunities for using sexed semen and semen of beef bulls in dairy herds. Journal of Dairy Science 100, 4161–4171. https://doi.org/10.3168/jds.2016-11333.

Faverdin, P., Guyomard, H., Puillet, L., Forslund, A., 2022. Animal board invited review: Specialising and intensifying cattle production for better efficiency and less global warming: contrasting results for milk and meat co-production at different scales. Animal 16,. https://doi.org/10.1016/j.animal.2021.100431 100431.

Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S., Englund, J.-E., 2011. The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. Agricultural Systems 104, 459–469.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock – A global

assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.
Grandl, F., Furger, M., Kreuzer, M., Zehetmeier, M., 2019. Impact of longevity on greenhouse gas emissions and profitability of individual dairy cows analysed with different system boundaries. Animal 13, 198–208. https://doi.org/10.1017/S175173111800112X.
Grossi, G., Goglio, P., Vitali, A., Williams, A.G., 2019. Livestock and climate change: impact of livestock on climate and mitigation strategies. Animal Frontiers 9, 69–76. https://doi.org/10.1093/af/vfy034.
Hristov, A.N., Ott, T., Tricarico, J., Rotz, A., Waghorn, G., Adesogan, A., Dijkstra, J., Montes, F., Oh, J., Kebreab, E., Oosting, S.J., Gerber, P.J., Henderson, B., Makkar, H. P., Firkins, J.L., 2013. Special topics–Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options. Journal of Animal Science 91, 5095–5113. https://doi.org/10.2527/jas.2013-6585.
IDF, 2015. A common carbon footprint approach for the dairy sector – The IDF guide to standard life cycle assessment methodology. Bulletin of the International Dairy Federation 479/2015, Brussels, Belgium.
Jamieson, A., (Ed.), 2010. Slakt och köttkvalitet. In: Nötkött. p. 189. Natur och Kultur, Stockholm, Sweden (in Swedish).
Knapp, J.R., Laur, G.L., Vadas, P.A., Weiss, W.P., Tricarico, J.M., 2014. Invited review: Enteric methane in dairy cattle production: quantifying the opportunities and impact of reducing emissions. Journal of Dairy Science 97, 3231–3261. https://doi.org/10.3168/jds.2013-7234.
Kristensen, T., Lund, P., 2012. Kvæg og klima. Udledning af klimagasser fra kvægbedriften med fokus på metan emissionen. Aarhus Universitet, DCA-Nationalt center for fødevarer og jordbrug. DCA report nr. 001. December 2011. Aarhus Universitet, Tjele, Denmark (in Danish).
Langford, F.M., Stott, A.W., 2012. Culled early or culled late: economic decisions and risks to welfare in dairy cows. Animal Welfare 21, 41–55. https://doi.org/10.7120/096272812x13345905673647.
Länsstyrelsen Västra Götaland, 2019. Bidragskalkyler för konventionell produktion. Retrieved on 12 November 2019 from https://www.lansstyrelsen.se/download/18.5e83a30f169d90292dfe5db/1555339884272/bidragskalkyler-konv-2019.pdf (in Swedish).
Lehmann, J.O., Mogensen, L., Kristensen, T., 2019. Extended lactations in dairy production: Economic, productivity and climatic impact at herd, farm and sector level. Livestock Science 220, 100–110. https://doi.org/10.1016/j.livsci.2018.12.014.
Nielsen, N.I., Volden, H., Akerlind, M., Brask, M., Hellwing, A.L.F., Storlien, T., Bertilsson, J., 2013. A prediction equation for enteric methane emission from dairy cows for use in NorFor. Acta Agriculturae Scandinavica Section a-Animal Science 63, 126–130. https://doi.org/10.1080/09064702.2013.851275.
Østergaard, S., Sørensen, J., Kristensen, A., 2000. A stochastic model simulating the feeding-health-production complex in a dairy herd. Journal of Dairy Science 83, 721–733.
Østergaard, S., Chagunda, M.G.G., Friggens, N.C., Bennedsgaard, T.W., Klaas, I.C., 2005. A stochastic model simulating pathogen-specific mastitis control in a dairy herd. Journal of Dairy Science 88, 4243–4257. https://doi.org/10.3168/jds.S0022-0302(05)73111-8.
Østergaard, S., Ettema, J.F., Kudahl, A.B., Tind Sørensen, J., 2010. Development of a Simherd web application for herd health advisors – experiences and perspectives. In: Proceedings of the International Workshop Farm Animal Health Economics, 14–15 January 2010, Nantes, France, pp. 14–15.
Pahmeyer, C., Britz, W., 2020. Economic opportunities of using crossbreeding and sexing in Holstein dairy herds. Journal of Dairy Science 103, 8218–8230. https://doi.org/10.3168/jds.2019-17354.
Pfuhl, R., Bellmann, O., Kuhn, C., Teuscher, F., Ender, K., Wegner, J., 2007. Beef versus dairy cattle: a comparison of feed conversion, carcass composition, and meat quality. Archiv Fur Tierzucht-Archives of Animal Breeding 50, 59–70. https://doi.org/10.5194/aab-50-59-2007.
Pritchard, T., Coffey, M., Mrode, R., Wall, E., 2013. Understanding the genetics of survival in dairy cows. Journal of Dairy Science 96, 3296–3309. https://doi.org/10.3168/jds.2012-6219.
Puillet, L., Agabriel, J., Peyraud, J.L., Faverdin, P., 2014. Modelling cattle population as lifetime trajectories driven by management options: A way to better integrate beef and milk production in emissions assessment. Livestock Science 65, 167–180.
Sehested, J., Gaillard, C., Lehmann, J.O., Maciel, G.M., Vestergaard, M., Weisbjerg, M. R., Mogensen, L., Larsen, L.B., Poulsen, N.A., Kristensen, T., 2019. Review: extended lactation in dairy cattle. Animal 13, s65–s74. https://doi.org/10.1017/S1751731119000806.
Stefani, G., El Faro, L., Santana, M.L., Tonhati, H., 2018. Association of longevity with type traits, milk yield and udder health in Holstein cows. Livestock Science 218, 1–7. https://doi.org/10.1016/j.livsci.2018.10.007.
Torres-Miralles, M., Sarkela, K., Koppelmaki, K., Lamminen, M., Tuomisto, H.L., Herzon, I., 2022. Contribution of High Nature Value farming systems to sustainable livestock production: A case from Finland. Science of the Total Environment 839,. https://doi.org/10.1016/j.scitotenv.2022.156267 156267.
Växa Sverige, 2019. Hälsoläget-reproduktion. Cattle Health Statistics. Retrieved on 6 April 2020 from: http://juverportalen.se/media/1271/vaexa-djurhaelsostatistik_2019_2020-1.pdf (in Swedish).
Växa Sverige, 2021. Husdjursstatistik 2021 – Cattle statistics Retrieved on 6 April 2020 from: https://www.vxa.se/globalassets/dokument/statistik/husdjursstatistik-2021.pdf (in Swedish).
Vellinga, T.V., de Vries, M., 2018. Effectiveness of climate change mitigation options considering the amount of meat produced in dairy systems. Agricultural Systems 162, 136–144. https://doi.org/10.1016/j.agsy.2018.01.026.
Vestergaard, M., Jorgensen, K.F., Cakmakci, C., Kargo, M., Therkildsen, M., Munk, A., Kristensen, T., 2019. Performance and carcass quality of crossbred beef x Holstein bull and heifer calves in comparison with purebred Holstein bull calves slaughtered at 17 months of age in an organic production system. Livestock Science 223, 184–192. https://doi.org/10.1016/j.livsci.2019.03.018.
von Soosten, D., Meyer, U., Flachowsky, G., Dänicke, S., 2020. Dairy cow health and greenhouse gas emission intensity. Dairy 1, 20–29.
Wallin, E., Nordström Källström, H., 2019. Mjölkproducenters uppfattning om nya avelsverktyg – En del av projektet Ökad lönsamhet med nya avelsverktyg i mjölkkobesättningarna. Urban and rural reports 2. Swedish University of Agricultural Sciences, Uppsala, Sweden (in Swedish).