

Sustainability aspects of milk production in Sweden

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Abstract

Resource use efficiency and economic initiatives point towards using less human-edible input in ruminant food production. This could also promote the nutrient-rich dairy products to consumers in comparison with alternative plant-based drinks. The global population is growing and food production will need to increase to feed more people in the future. The Swedish government has launched a national food strategy, which aims to move Swedish food production towards self-sufficiency and sustainability, and greater exports. Simultaneously, strong economic development has stimulated consumers to request more high-value foods, such as meat and refined dairy products. At the same time, public opinion states that today's food production from ruminants is negative for the environment and contributes to climate change. This review assesses some aspects of dietary ingredient composition and feeding choices that can contribute to making Swedish dairy production more sustainable. Efficient dietary methane mitigating strategies can decrease emissions of greenhouse gases in line with European Union targets and avoid major changes in dietary consumption patterns of meat and milk from ruminants. Although feeding management seems to be the most important approach to decrease nitrogen losses, rational use of fertilizers and improved manure management practices on dairy farms should also be considered to decrease the impact of nitrogen losses to the environment.

KEYWORDS

agro-industrial by-products, dairy production, food production, grass, greenhouse gases, resource efficiency

1 | INTRODUCTION

The geographical location and extended north-south gradient (55–69°N) of Sweden results in considerable variation in farming conditions. In addition, variations in topography, contrasts between coastal and inland climates and agricultural policies influence the distribution of crops. Crop production is strongly dominated by cereals (mainly barley) and grass leys. The proportion of leys increases

towards the north of Sweden, where it is the dominant crop on arable land. Grass is also the major single crop in Sweden as a whole, occupying more than 1 million ha of agricultural land (close to half of all agricultural land) and producing an average annual yield (1990–2018) of almost 4 million tons of dry matter (DM) (Swedish Board of Agriculture, 2019). The long, light days in summer allow grass plants to build up energy-rich carbohydrates from photosynthesis for almost 24 hr per day, while the relatively low temperature in early

An earlier version of this article was a keynote presentation at the 28th General Meeting of the European Grassland Federation hosted by Finland in 2020 (www.europeangrassland.org/).

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summer reduces lignification, promoting a potential high feeding value, but forage needs to be conserved for supply all year round. The cold winters are also beneficial contributing to a generally lower pressure of pests. Domestic milk production based on grass will play an important role in the future in Swedish agriculture, food production and food industry.

Long-term fluctuations in grain prices on the world market have raised economic concerns and promoted the production and feeding of high-quality forages in ruminant production systems. Despite this, intensive milk production in Sweden is still supported by high amounts of concentrate feed (Swensson et al., 2017). Greater use of concentrate feed means that fertile agricultural land is devoted to animal feed production and that more pesticides are needed, resulting in a greater environmental footprint. A large proportion of feed resources fed in ruminant production systems could be used directly as human foods, or utilized with higher efficiency in poultry and pig production. Additionally, changes in biodiversity and ecosystem services following changes in the land use are rarely measured and accounted for in the food value chain seeking to meet consumer preferences and demands (Cederberg et al., 2018).

The global population is growing and, although food production has increased markedly in the past 50 years, it will need to increase significantly to feed a population of more than 11 billion people by the next century. Even today, not everyone has access to sufficient protein and energy from their diet (FAO, 2018). At the same time, strong economic development is influencing the global demand for food products. Swedish food consumption and food trade patterns have changed in recent decades, mainly towards increased consumption of high-value foods with a larger environmental footprint, such as meat and refined dairy products (in contrast with low-value foods such as fresh milk, flour and potatoes). These changes impose a measurable burden of food consumption and trade on the environment, e.g. through greater use of agrochemicals and greenhouse gas (GHG) emissions (Cederberg et al., 2019). According to Bryngelsson et al. (2016), methane (CH₄) and nitrous oxide (N₂O) emissions from agriculture must be reduced to meet an emissions allowance in line with European Union (EU) targets of 300–1300 kg CO₂-equivalents per capita and year by 2050.

In 2017, the Swedish government launched a National Food Strategy (Government Bill 2016/17:104) to increase domestic food production by 2030 through active food policy (Regeringskansliet, 2017). The strategy involves the entire food supply chain and is intended to secure increased and sustainable food production for global food security, higher self-sufficiency and increased export. Food production from ruminants is well-suited for Swedish conditions, but will have to adapt to meet climate targets and employ innovative marketing to maintain consumer confidence in safe and low-emitting food. Additionally, Sweden has committed to realize several environmental goals until 2045 of which reduced climate impact, non-toxic environment, no eutrophication and sustained diversity of the agricultural landscape are of most relevance for agricultural food production (Swedish Board of Agriculture, 2021). This paper deals with some nutritional and future aspects of Swedish dairy production systems from a science-based

view, which, if implemented, could contribute to more sustainable milk production.

2 | SWEDISH DAIRY PRODUCTION SYSTEMS

Swedish agriculture is undergoing a continuous structural transformation. It is most evident in milk production where the increased pressure of profitability and productivity has uniformly developed towards increased yield and a reduced number of dairy farms. Today there are around 3,000 dairy farms in Sweden, but in 1976 there were more than 50,000. However, the amount of milk produced has decreased by only half of the decrease in the number of dairy cows in the country (in percentage terms), as individual farms have expanded considerably, while also obtaining significantly more from every hectare and from every animal. For example, in 2019, 2015, 2010 and 2002 one hectare of ley yielded an average of 5,240, 5,210, 4,690 and 4,380 kg DM/ha, respectively. An average dairy cow today produces about 8,700 litres of milk per year, but in 1970 the corresponding figure was only around 4,000 litres (Swedish Board of Agriculture, 2019). Overall milk production has decreased 16% in Sweden between 1999 and 2018, and the main reasons given are high investment costs for medium-sized farms and high costs for feed. Import of red meat and cheese has simultaneously increased (IVA, 2019).

At the same time, the number of dairy cows has decreased twice as much as the decline in milk production (Swedish Board of Agriculture, 2019). This fits relatively well with the doubling of the average annual milk production per cow in Sweden. However, Guinguina (2020) showed that, at a population level, milk production has been increasing at a decreasing rate from 3.1% to 0.6% between 1974 and 2018 (Figure 1), which clearly illustrates that increases in efficiency will not be reached from increased milk production anymore, rather only from increased feed efficiency on population level.

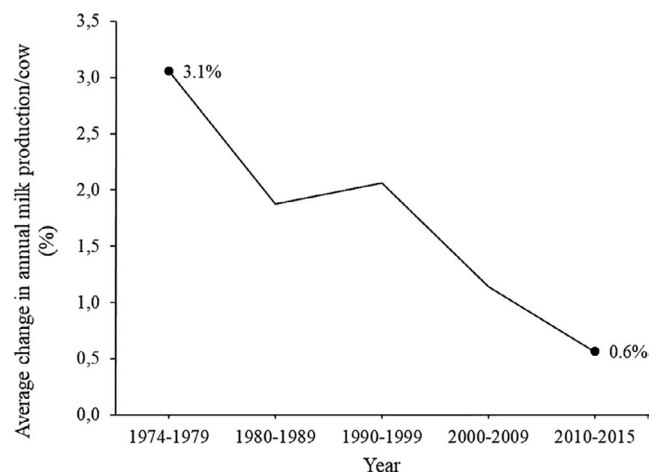


FIGURE 1 The average change in annual milk production per cow in Sweden (from Guinguina, 2020)

From a global perspective, a large proportion of the area currently used for food production within the European Union is estimated to lose its food-producing capacity, due to climate change, salinity and erosion. On the contrary, Sweden will still have access to the most important natural goods like fields, pasture and water for food production. However, in large parts of Sweden, for mainly climate reasons (short growing season) it is only possible to grow forage and feed-grade grain which emphasizes the importance of sustained food production from ruminants. Despite the good conditions for milk and meat production in Sweden, the self-sufficiency of milk and dairy products are only at about 74 percent (of which cheese just over 40 percent) and beef of 54 percent (IVA, 2019).

Further food production from ruminants is characterized by low efficiency of resource use, despite grass providing the majority of total DM intake in dairy cow diets. Ruminants have a low feed conversion ratio and a long reproduction interval, resulting in a large proportion of dietary energy being used for maintenance. Despite this, ruminants have been shown to perform better than monogastrics in comparison to human-edible efficiency of energy and protein for different livestock production systems (Gill et al., 2010) (Table 1). Depending on diet composition, even greater differences in edible feed conversion ratio (eFCR) have been observed. Pang et al. (2018) fed diets consisting of grass silage and concentrate in a ratio of 661:339, and reported eFCR for energy and protein of between 0.92 and 4.56 MJ/MJ edible input and between 0.94 and 4.15 g/g edible input, respectively, when a by-product-based concentrate replaced a conventional grain-based concentrate in dairy cow diets. There were no effects of concentrate source on feed intake, milk production, diet digestibility or CH₄ emissions, and there were indications of a better energy status in cows fed the concentrate made of by-products compared with the grain-based concentrate. Notably, the eFCR for both energy and protein was greater when the cows were fed high- rather than low-digestibility grass silage (Pang et al., 2018).

Guinguina (2020) evaluated the effects of reducing the dietary starch content by replacing cereal grain with a fibrous by-product mixture, on the performance of early-lactation dairy cows fed a grass silage-based diet. They found that feed intake, milk yield and energy status were not affected by concentrate type, and observed

substantial improvements in eFCR. Ertl, et al. (2015) observed a higher propionate content and lower acetate to propionate ratio in vitro for a diet supplemented with by-products compared with a control concentrate mixture. They attributed this to more easily fermentable fiber such as pectin and hemicellulose in the by-products, which was assumed to stimulate propionate formation, and to higher abundance of *Prevotella*. They also speculated that by-products, which stimulate propionate formation and gluconeogenesis in dairy cows may be beneficial, particularly during early lactation, through improved energy efficiency (Ertl, et al., 2015). Similarly, Guinguina (2020) recorded lower CH₄ emissions from dairy cows fed concentrate in the form of by-products rather than cereal grains.

Feeding agro-industrial by-products is often suggested as a viable option to improve sustainability in terms of human-edible output in dairy production (Dann et al., 2014; Ertl et al., 2015, 2016; Whelan et al., 2017). Total recorded use of agro-industrial by-products in commercial feeds for farm animals was 535,989 ton in Sweden in 2014 (Swedish Board of Agriculture, 2014). Up to 80% of these by-products were fed to ruminants and most were produced domestically. In Sweden, imported rapeseed by-products comprise 20% of the total amount of agro-industrial by-products used in ruminant production systems, while at the same time there is a surplus of dried distillers' grain, which is exported to Europe (Swedish Board of Agriculture, 2014). Efficient use of non-human edible feed resources produced locally or nationally could improve the resource use efficiency of dairy food production in Sweden.

3 | DAIRY FOOD CONSUMPTION PATTERNS AND CLIMATE CHANGE

Worldwide consumption of ruminant meat and dairy products are prospected to increase due to a growing global population that will demand nutritious food. Also food trade patterns in developed countries indicate that consumers will request more meat and refined dairy products (FAO, 2018). However, there are deviations from these dietary preferences e.g. the plant-based food industry has rapidly developed in recent years. Plant-based food is an industry incentive itself, but also several dairy companies have broadened their product portfolio to include plant-based beverages to keep consumers and to increase profit. There is an ongoing debate about the relative sustainability of animal- versus plant-based food sources driven by the different food category contribution to GHG emissions, the main contribution to climate change through global warming. Despite that, recent satellite data suggest that the fossil fuel industry contributes twice as much to CH₄ emissions than agriculture (Howarth, 2019). The human dietary changes are suggested by several researchers as an inevitable and efficient mean to fulfil European Union (EU) climate targets of emission allowances per capita to meet the global 2°C limit (European Commission, 2011). Hedenus et al. (2014) stated that due to lack of expected reductions in other GHG-emitting sectors, like energy, improved technology and productivity of the agricultural sector is not enough to prevent

TABLE 1 Comparative efficiency of different livestock production systems in the USA (adopted from Gill et al., 2010)

Product	Energy efficiency		Protein efficiency	
	Total ^a	Human-edible ^b	Total ^a	Human-edible ^b
Milk	0.25	1.07	0.21	2.08
Beef	0.07	0.65	0.08	1.19
Pigs	0.21	0.30	0.19	0.29
Poultry meat	0.19	0.28	0.31	0.62

^aTotal efficiency calculated as outputs of human-edible energy and protein divided by total energy and protein inputs.

^bHuman-edible efficiency calculated as outputs of human-edible energy and protein divided by human-edible inputs.

global warming, and additionally meat and dairy consumption should be substantially reduced. Bryngelsson et al. (2016) predicted that the Swedish food-related mitigation of CH₄ and N₂O can be reduced enough to meet the EU 2050 climate targets, but demand cuts by 50% or more in ruminant meat consumption. Continued consumption of non-ruminant meat or dairy products can be accommodated within the climate targets, but high dairy consumption is only compatible with the 500 kg CO₂-eq target if there are substantial advancements in technology. Short-term technology advancements of relevance should aim at reducing emissions from manure, decrease fertilizer use in crop production and dietary mitigation of enteric CH₄ production.

Grant and Hicks (2018) made life cycle assessment analysis of almond, soy and dairy milk. The results showed that the choice of functional unit had a strong influence of the outcome of the analysis. Despite long transportations of almond and soy, dairy milk showed higher impact when using a volumetric functional unit than when compared with a nutritional functional unit of kg protein. Smedman et al. (2010) compared beverages in terms of nutrient density related to an assessment of the products GHG emission (Figure 2). Low nutrient densities of carbonated water, soft drink, beer, red wine and oat drink gave a low index value, orange juice and soy drink had similar index, and dairy milk clearly the highest due to the higher nutrient density. In a recent publication of the importance of milk consumption during different human life stages Givens (2020) concluded that replacement of dairy products with plant-based food has to be made based on relative functionality, and emphasized important traits like hypotensive and muscle protein synthesis stimulation effects rather than simple comparisons of nutrient content.

Cederberg (2017) pointed out increasing consumer interest in environmentally friendly milk and beef production in grass-based certified systems that can achieve long-term sustainability. Swedish dairy production is based on grass in crop rotation and grazing of both arable areas and permanent grasslands. Most of the production utilizes land less suitable for growing cereals or annual legumes. Dairy production and grasslands prevent afforestation thus maintaining landscapes and biodiversity. In a global comparison, Swedish dairy production is characterized by efficient nutrient management,

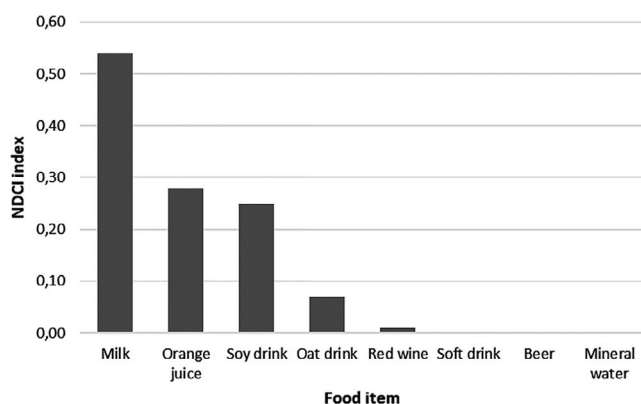


FIGURE 2 Nutrient density to climate impact (NDCI) index of different beverages (from Smedman et al., 2010)

low use of inputs such as chemical fertilizers, crop-protection and antibiotics. The dairy farms are also crucial for rural economic livelihoods as every farm creates and maintains an average of seven jobs, mainly in the rural areas.

Additionally, a further decrease in milk production and consumption will increase the climate impact from ruminant meat production in Sweden, since beef from dairy cows constitute about 2/3 of Swedish beef production. For every litre of milk, 70 grams of beef is produced with the current production system in Sweden, lowering climate impact from Swedish beef production by 35%–50% compared to specialized beef production (Anna-Karin Karlsson, Norrmejerier, personal communication). It is important that these values of Swedish milk production are measurable and communicated with policy makers and consumers. An initiative that could be made from dairy companies is to define and award sustainable dairy farms giving benefit according to a low-input of human-edible feed, circular systems, and good animal health and welfare. Schader et al. (2015) predicted that food can be produced from ruminants fed a grassland-based diet without any human-edible concentrate supplementation in the future. It was suggested that enough food will be produced, and such food system will also reduce environmental impacts. Schader et al. (2015) stressed the value of grasslands as carbon sink and suggested that the challenge to livestock feed industry will be to further improve the use of agricultural residues and agro-industrial by-products to produce high-quality feedstuffs.

4 | OPTIMIZING PRODUCTION BY PRECISION FEEDING

The most basic way to decrease emissions is precision feeding i.e. formulate rations to meet nutrient requirements to avoid both under- and overfeeding, and maximize production. Alternatively expressed, to optimize microbial protein synthesis or improve efficiency of dietary nutrient use to decrease CH₄ production per unit of animal product (Hristov et al., 2013). Hristov et al. (2013) also emphasized the need for improving feed analyses and forage quality as efficient mitigation strategies. These strategies are relevant for both developing and developed countries, but the effect is likely greater in developing countries.

Grass yield as well as nutritional and ensiling quality are important factors in optimizing ruminant livestock production systems. It is established that early-harvested grass from spring growth generally produces highly digestible silage that can support higher milk yield with less concentrate feed than grass harvested at a more mature stage (Ferris et al., 2001; Randby et al., 2012; Rinne et al., 1999). Randby et al. (2012) fed early harvested grass silage with 747 g digestible organic matter (OM)/kg DM, with and without concentrate supplementation, and found that total DM intake and milk yield increased with increased concentrate supplementation. They cited metabolizable protein deficiency in early lactation as the main reason for the reduction in milk yield of cows fed silage only. To optimize forage utilization on a dairy farm, it is important to know

the quantitative effects of digestible OM concentration (*D*-value) and harvest time of grass silage on intake and milk production, and how these responses influence other factors, such as production level and concentrate supplementation (Pang, 2018). Fermentation-related factors are indicative of the efficiency of forage conservation and of modifications in the carbohydrate and nitrogen fractions during conservation, and affect silage intake (Huhtanen et al., 2007; Krizsan and Randby, 2007). The Swedish growing season for grass, i.e. average temperature above +5°C, is now more than 10 days longer than it was 50 years ago (Gustavsson, 2017). This extended growing season is generating interest in using leys for forage production, including new varieties, and is creating demand for continued knowledge of forage nutritive value and harvesting regimes.

4.1 | Intake

Feed intake is the most important single nutritive factor influencing production of dairy cows (Huhtanen, Rinne et al., 2011; Mertens, 1994). Variations in the nutrient supply for ruminants are mostly related to forage characteristics, which is defining the intake potential (Huhtanen et al., 2007; Mertens, 1994). Feed is also often the largest single cost for dairy farmers. It is not always clear whether a given feeding regimen/diet or the inherent potential of the cow is limiting milk production. Friggens et al. (1998) conducted a cross-over trial examining the effect of feed quality on the relationship between intake and stage of lactation in dairy cows, and found that milk yield was significantly lower for cows fed the lower-energy diet than for cows offered the high-energy diet. After cross-over of diets, the cows adapted their milk yield to the quality of the new diet, and not to their previous level of production.

Krizsan et al. (2014) used individual milk yield data from dairy cow cross-over trials to evaluate feed intake prediction models. In their meta-analysis approach, individual milk yield data from previous period (prospective), observed period (retrospective) and average overall periods were combined with current feed data in intake prediction models for dairy cows and were compared with observed intake in the current period. They concluded that using observed milk yield as a model input in predictions of feed intake can be substantially affected by dietary factors. However, using a standardized milk yield according to Huhtanen, Rinne, et al. (2011) improved the predictions of feed intake and provided a more robust model reflecting the potential of the cow (Krizsan et al., 2014). Milk yield as a model input in intake predictions can be substantially affected by current diet, generating errors in estimates of future feed intake and milk production if the economically optimal diet deviates from the current diet (Krizsan et al., 2014).

4.2 | Digestibility

Faecal energy is a greater and more variable loss of feed gross energy than CH₄ and urinary energy, and therefore accurate determination

of digestibility is essential in determination of silage metabolizable energy concentration and forage intake potential. Variations in forage OM digestibility (OMD) cannot be satisfactorily predicted from feed chemical composition (Huhtanen et al., 2006). In *in vivo* approaches, the feeding value of diets is determined from digestibility coefficients, determined in trials with sheep fed a maintenance level of intake, and proximate analysis. However, due to the large amounts of forage and labour required when conducting digestibility trials, different *in situ* and *in vitro* methods have been developed and successfully related to *in vivo* data on OMD. Krizsan et al. (2012) compared the use of different *in vitro* and *in situ* methods in empirical and mechanistic predictions of *in vivo* OMD for a wide variety of forage types. They achieved the smallest prediction error of forage *in vivo* OMD by using *in situ*-determined indigestible neutral detergent fibre (iNDF) content when forage-specific equations for lucerne and straw were used. Krizsan et al. (2015) showed that the iNDF concentration is not altered during ensiling of grass (Figure 3). A close relationship between near-infrared reflectance spectroscopy (NIRS) values and iNDF in grass silage has been reported by Nousiainen et al. (2004). These results support the development of a high-throughput NIRS application by farm service laboratories to predict forage OMD based on *in situ*-determined iNDF. Huhtanen et al. (2010) were able to predict forage *in vivo* OMD from iNDF and NDF with a prediction error of only 0.008 g/kg.

Pang (2018) found that every 10 g/kg DM increase in silage digestible OM/kg DM (*D*-value) resulted in a 0.39 and 0.24 kg increase in milk yield in cows fed primary growth and regrowth silage, respectively. These values correspond to the increase of 0.26 kg by Huhtanen (1994), 0.27 kg by Rinne (2000) and 0.30 kg by Pang et al. (2019). Milk yield is positively related to dietary intake of

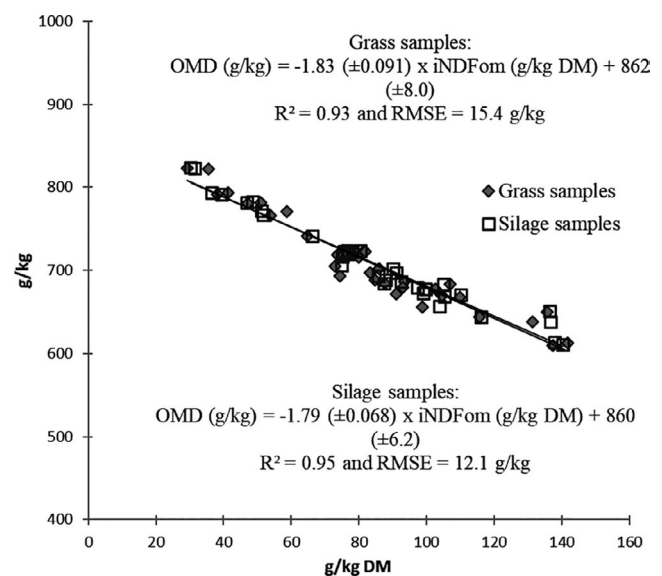


FIGURE 3 Linear relationship between *in vivo* organic matter digestibility (OMD) and ash-free indigestible neutral detergent fibre (iNDFom) (both g/kg dry matter (DM)) in grass and corresponding silage samples. Coefficient of determination (R^2) and root mean square error (RMSE) of the regression equations are given (from Krizsan et al., 2015)

metabolizable energy and the response to changes in silage *D*-value is positively correlated with intake of metabolizable energy (Pang et al., 2019). The response of 0.109 kg energy-corrected milk yield per MJ additional metabolizable energy intake reported by Pang et al. (2019) compares well with the 0.114 kg energy-corrected milk yield per MJ found by Huhtanen et al. (2003). This suggests that the additional metabolizable energy from increased feed intake resulting from improved silage quality is used with at least the same relative efficiency for milk production as additional metabolizable energy from concentrates.

Flaten (2002) and Gunnarsson et al. (2014) identified economic initiatives related to choice of harvesting strategy following early harvest of the spring growth grass. The profit of farms applying a three-cut system was greater than that of farms applying a two-cut system, despite the greater costs of crop management and labour input for the three-cut system. Flaten (2002) also found that more expensive concentrate feeds have to be supplied in Norwegian dairy production when the two-cut system was applied. This is in line with suggested greater yield of grass in three-cut systems (Martinsson and Eriksson, 2010) and good milk

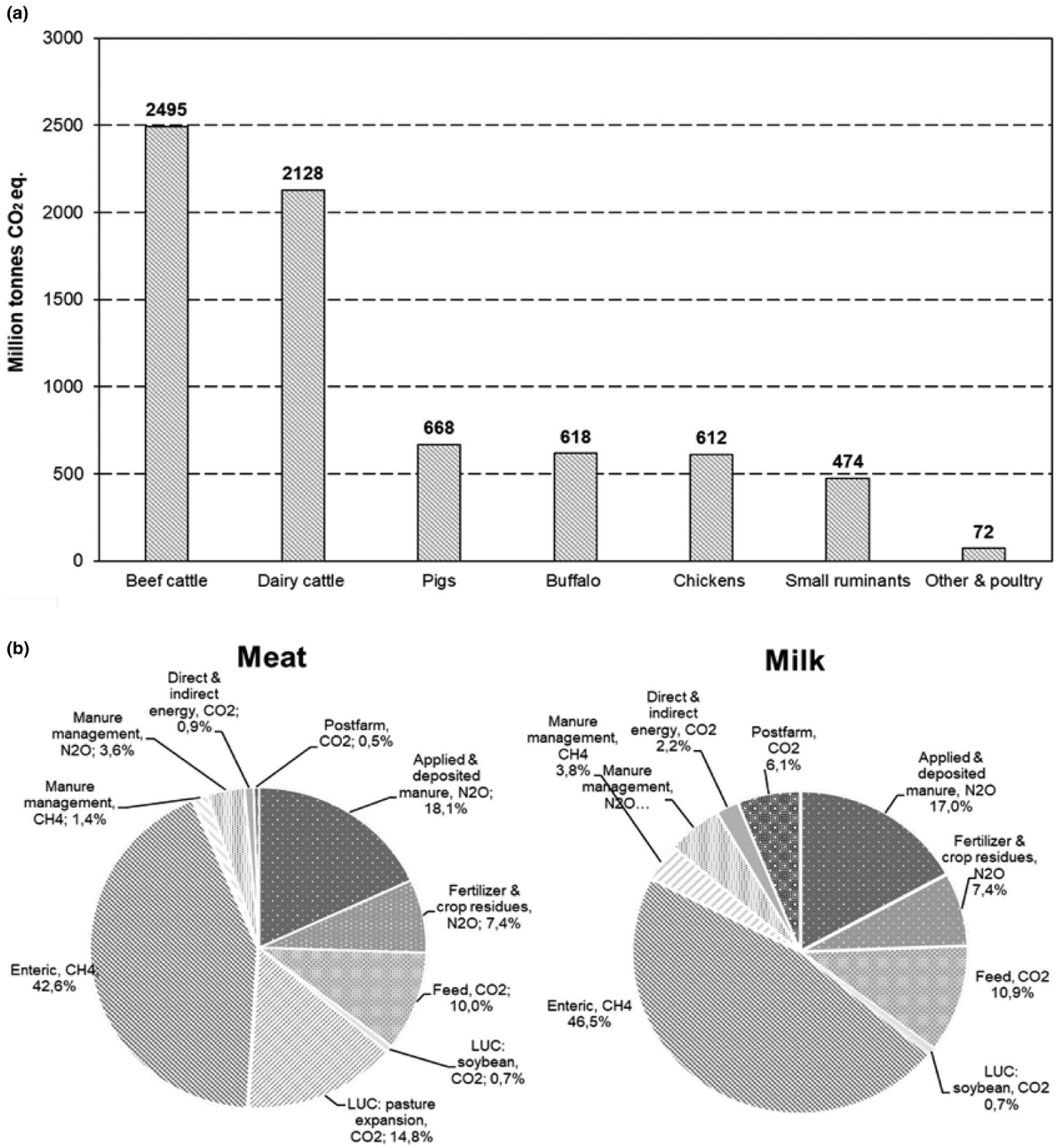


FIGURE 4 (a) Global estimated emissions by species. (b) Emissions from cattle milk and beef supply chains. Source: GLEAM (modified from Gerber et al., 2013)

yield response of cows fed third-cut silage (Pang, 2018; Sairanen et al., 2016).

Dietary CH₄ mitigation strategies.

Today, livestock supply 13% of the energy in human diets (Smith et al., 2013) and are responsible for around 14% of total anthropogenic GHG emissions (7.1 Gt CO₂-equivalents per year; Gerber et al., 2013). It is clear that cattle (beef and dairy) produce more total GHG emissions than other animal species (Figure 4). Enteric fermentation in cattle contributes most to these GHG emissions, followed by N₂O emissions from soil and manure management (Gerber et al., 2013). Since global production of meat is projected to increase from 229 million ton in 2000 to 465 million ton in 2050, and milk production is projected to increase from 580 to 1,043 million ton, it is likely that ruminants will continue to contribute to GHG emissions in the future, even if monogastric farm animals meet much of the increase in demand for meat. Regional average CH₄ emission intensity ranges from 1.2 to 7.5 kg CO₂-eq./kg of milk (FAO, 2010). This range reflects the variable intensity and productivity of global livestock production and indicates that GHG emissions could still be reduced through increases in agricultural productivity and efficiency. Bryngelsson et al. (2016) concluded that consumption pattern likely has to change, and that high dairy consumption is only compatible with the targets if there are substantial advances in technology. Reducing food waste would play a minor role in meeting the climate targets, lowering emissions by only an additional 1%–3%.

Hedenus et al. (2014) suggested that future implementation of efficient mitigation technologies can avert the need for dietary change. In future predictions, they included dietary mitigation of enteric CH₄ from supplementation of fat, estimated to reduce emissions by up to 20% in non-pasture fed animals. Chagas et al. (2019) evaluated different dietary mitigation strategies in a large in vitro experiment that included chemical inhibitory compounds, plant-derived inhibitory treatments and different potentially CH₄-reducing diets. They found that inclusion of the natural anti-methanogenic red seaweed *Asparagopsis taxiformis* at a level of 0.5 mg/g (OM basis) resulted in almost complete inhibition of CH₄ production, with little impact on rumen fermentation parameters. These results are in line with earlier findings that production of CH₄ was decreased by 84.7% at an *A. taxiformis* inclusion level of 1 mg/g (OM basis), while doses greater than 2 mg/g (OM basis) decreased CH₄ production by more than 99% (Machado et al., 2016). A recent in vivo experiment by Stefanoni et al. (2019) involving inclusion of *A. taxiformis* at 0.5 g/kg of DM intake decreased CH₄ emissions in lactating dairy cows by 80%, with no negative effects on DM intake or milk yield. These results suggest that natural bioactive compounds produced by *A. taxiformis* can act as a strong natural inhibitor of CH₄ production and could form part of an effective strategy to mitigate CH₄ emissions caused by domesticated ruminants. The effect of *A. taxiformis* on milk quality is at present investigated in in vivo experiments with dairy cows, and despite the strong promising inhibitory effect on CH₄ the total environmental gain will likely be diminished when regarding an upscaling and production of a tropical seaweed for all dairy cows in northern Europe.

5 | NITROGEN EFFICIENCY

In ruminant production systems, nitrogen (N) inputs from fertilizer, feed and manure have been identified as the major sources of N excretion and associated environmental impacts (Powell et al., 2013). European data suggest that agriculture is the main contributor to N pollution, accounting for approximately 78% of total N entering surrounding ecosystems (Sutton, Billen, et al., 2011). The N in manure deposited on pasture and on flooring in free stall housing can run off into surface water, leach into soil or volatilize to gases such as ammonia, which affects air quality, and N₂O, a potent GHG with a much higher CO₂ equivalence factor (298) than CH₄ (IPCC, 2007). The main sources of N₂O from agriculture are connected with nitrification and denitrification processes in soil. Farms emit N₂O that is originating mostly from N fertilizers (organic manure or inorganic fertilizers), direct N deposition by confined animals or manure storage (Adler et al., 2015). There is also enteric N₂O release by ruminants, but it has a 9-fold lower impact on total N₂O emissions than manure (Prusty et al., 2014).

The proportion of feed N consumed by dairy cows that is captured in milk is on average 28%, representing poor efficiency of converting feed N into milk (Foskolos and Moorby, 2018). Thus, increased N use efficiency (NUE; feed N consumed that is secreted as milk N) in ruminant production systems can be a key factor to improving N management and reducing the environmental impact (Sutton, Howard, et al., 2011). Reductions in dietary crude protein (CP) or feeding CP:energy balanced diets can increase the NUE and can be considered as a feasible N mitigation option (Hynes et al., 2016). Kidane et al. (2018) reported that gradually decreasing dietary CP from 175 to 130 g/kg DM increased NUE and reduced urinary N excretion without affecting production. Comparatively, Colmero and Broderick (2006) reported that feeding more than 165 g CP/kg diet DM did not increase yield of milk and protein, while urinary N excretion increased linearly with increased dietary CP concentration. Although feeding management seems to be the most important approach to decrease N losses, rational use of fertilizer and improved manure management practices on dairy farms should also be considered to decrease the N impacts on the environment.

6 | CONCLUSIONS

Milk production in Sweden holds a high standard, but is currently based on resource-intensive dairy feed production with consequences for the environment. Milk yield per cow has more than doubled within the past half century. It is likely that the future possibility to decrease the environmental footprint of dairy production in Sweden through increased productivity will be marginal. Dairy cows have the ability to utilize human-inedible resources and can sustain a large part of their milk production on high-quality grass-based diets. It is crucial to develop productive sustainable grasslands through better management, feed evaluation and improved varieties, which can exploit changes in climate and seasonal variations to

increase productivity. Grass-based ruminant food production with implementation of efficient methane mitigation strategies could be a sustainable part of an ecological carbon cycle and preserve important agricultural ecosystem services. Future evaluation of sustainable milk production should encounter additional values like animal welfare, biodiversity, land use and edible resource use efficiency, but also emphasize consumer interests and communication.

AUTHOR CONTRIBUTION

Sophie Julie Krizsan: Conceptualization (lead); Investigation (lead); Project administration (lead); Resources (lead); Writing-original draft (lead). Juana Chagas: Conceptualization (supporting); Data curation (supporting); Investigation (supporting); Writing-original draft (supporting). Edward Garcia: Conceptualization (supporting); Investigation (supporting); Resources (supporting); Visualization (supporting); Writing-original draft (supporting). Degong Pang: Conceptualization (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Project administration (supporting); Resources (supporting); Visualization (supporting); Writing-original draft (supporting).

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How to cite this article: Krizsan SJ, Chagas JC, Pang D, Cabezas-Garcia EH. Sustainability aspects of milk production in Sweden. *Grass Forage Sci.* 2021;76:205–214. <https://doi.org/10.1111/gfs.12539>