Greenhouse Gas Emissions from Swedish Milk Production

- Towards Climate-Smart Milk Production

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Abstract
Greenhouse gas (GHG) emissions from food production represent 19-29% of global anthropogenic GHG and the dairy sector alone is estimated to contribute around 3%. This thesis assessed GHG estimates for milk production (*i.e.* milk carbon footprint (CF)) in a life cycle perspective. Uncertainties in milk CF were examined for two contrasting milk production systems (an intensive system in Sweden (SE) and a more extensive system in New Zealand (NZ)) and variations in milk CF estimates between Swedish dairy farms were determined. GHG emissions from feed production and enteric fermentation, representing around 85% of milk CF, were estimated on herd level for different feeding strategies related to regional conditions for feed cultivation. The methodology used was Life Cycle Assessment with the system boundary 'cradle to farm gate'.

National average milk CF for SE and NZ was estimated to be 1.16 and 1.00 kg carbon dioxide equivalents (CO_2e)/kg energy corrected milk (ECM) respectively, with uncertainty of approximately ±30% due to uncertainties in emissions factors predicting enteric CH_4 and soil N_2O emissions, which were among the most influential parameters for milk CF estimates. The most influential variable was feed intake. Milk CF was found to vary by approximately ±17% between Swedish dairy farms due to differences in management practices, indicating potential for reducing GHG emissions on farm level. GHG emissions from different feeding strategies varied between 0.42 and 0.53 kg CO_2e/kg ECM for feed production, and between 0.50 and 0.52 kg CO_2e/kg ECM for corresponding enteric CH_4. Thus differences in feeding strategy affected GHG emissions from feed production more than enteric CH_4 production. Roughage production contributed >50% of the emissions and grass silage CF varied markedly (by 17%) between regions and influenced the overall emissions. It was also influenced by feed losses from silage storage and feeding. Grass silage nutrient quality also influenced emissions from feed production and enteric CH_4 production. Replacement animals contributed approximately 20% of these GHG.

The large uncertainties in milk CF indicate that values should not be compared unless estimated with harmonised methods and that caution is needed when they are used in mitigation studies. Efficient use of all resources is an important general mitigation measure. Measures with varying effects need to be evaluated at farm level.

Keywords: carbon footprint, farm level, feed production, greenhouse gases, life cycle assessment, land use, milk production, mitigation, NorFor, uncertainties, variations

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Växthusgasutsläpp från Svensk Mjölkproduktion

Sammanfattning

Av världens totala växthusgasutsläpp orsakade av mänsklig påverkan står matproduktionen uppskattningsvis för 19-29 % och enbart mjölkproduktionen för ca 3 %. Den här avhandlingen har studerat mjölkens klimatpåverkan i ett livscykelperspektiv (även kallat mjölkens ”carbon footprint” (CF)) med metoden för livscykelanalys (LCA) och systemavgränsningen ”vagga till gårdsgrind”. Beräkningar av växthusgaser (VHG) från biologiska system innebär stora osäkerheter. Hur dessa påverkar mjölkens CF studerades med Monte Carlo analys för mjölkproduktionssystem i Sverige (SE) och Nya Zeeland (NZ). Samma metod användes för att uppskatta variationer i mjölkens CF bland svenska mjölkgårdar till följd av skillnader i management och resultat. Då huvuddelen av utsläppen (ca 85 %) utgörs av metan (CH_4) från djurens fodersmältning och VHG från produktionen av foder, studerades dessa utsläppskällor separat för olika sammansättningar av foderstater, representerade av fem regioner, med två olika kvaliteter av vallensilage. Beräkningarna inkluderade även rekryteringskvigor.

Medelvärdet för mjölkens CF i SE och NZ beräknades till 1,16 respektive 1,00 kg koldioxidekvivalenter (CO_2e)/kg energikorrigerad mjölk (ECM) med ca ±30 % osäkerhet till följd av stora osäkerheter i emissionsfaktorerna för CH_4 från fodersmältning och lustgas (N_2O) från mark. Dessa parametrar, tillsammans med djurens foderintag, var de som mest påverkade mjölkens CF. Variationen mellan gårdar i SE beräknades till minst ±17 %, vilket indikerade att det finns en potential att minska VHG utsläpp från svenska mjölkgårdar. Utsläpp av VHG från produktionen av foder till respektive foderstat beräknades till motsvarande 0,42-0,53 kg CO_2e/kg ECM och CH_4 utsläppen från fodersmältningen till 0,50-0,52 kg CO_2e/kg ECM. Detta visade att produktionen av foder till olika typer av foderstater sannolikt påverkar de totala utsläppen mer av vad foderstatens inverkan på CH_4-utsläpp från fodersmältningen gör. Mer än 50 % av foderstatens CF utgjordes av VHG-utsläpp från produktion av vallensilage, vilka också varierade mellan regionerna och därmed hade en betydande inverkan på foderstatens CF. På grund av en fjärde vallskörd bidrog den förbättrade ensilagekvaliteten till en ökning av de sammanlagda VHG-utsläppen, trots att den bidrog till minskade utsläpp av CH_4 från fodersmältningen. Rekryteringskvigorna stod för ca 20 % av VHG-utsläppen från foderproduktion och CH_4 från fodersmältningen.

Stora osäkerheter i beräknade CF för mjölk (och andra agrara produkter) innebär att dessa endast bör jämföras om beräkningar utförts på ett likvärdigt sätt samt användas med försiktighet vid utvärdering av åtgärder för att minska VHG utsläpp på gårdsnivå. Eftersom förutsättningar för foderproduktion skiljer mellan regioner och gårdar måste foderstatens sammansättning relaterat till åtgärder att minska VHG-utsläpp utvärderas på gårdsnivå. En generell åtgärd på gårdsnivå är dock ett effektivt resursutnyttjande i alla delar av mjölkproduktionskedjan.

Nyckelord: Carbon footprint, gårdsnivå, foderproduktion, växthusgaser, osäkerheter, variationer, livscykelanalys, markanvändning, mjölkproduktion, åtgärder, NorFor

Dedication

To my godchildren
    Jack & Tuva

and all children whose future is our responsibility

Nog finns det mål och mening i vår färd -
men det är vägen, som är mödan värd
    Karin Boye

Yes, there is goal and meaning in our path -
but it's the way that is the labour's worth
    translation by David McDuff

Contents

List of Publications

This thesis is based on the work contained in the following Papers, referred to by Roman numerals in the text:

I Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S. and Englund, J-E., 2011. The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. *Agricultural Systems* 104(6), 459-469

II Henriksson, M., Flysjö, A., Cederberg, C. and Swensson, C., 2011. Variation in carbon footprint of milk due to management differences between Swedish dairy farms. *Animal* 5(9), 1474-1484.

III Henriksson, M., Cederberg, C and Swensson, C., 2012. Impact of cultivation strategies and regional climate on greenhouse gas emissions from grass/clover silage. *Acta Agriculturae Scandinavica Section A* 62(4), 233-237.

IV Henriksson, M., Cederberg, C and Swensson, C., 2014. Carbon footprint and land requirement for dairy herd rations - impacts of feed production practices and regional climate variations. *Animal, doi:10.1017/S1751731114000627, published online: 25 mars 2014*

V Henriksson, M., Swensson, C. and Åkerlind, M., 2012. The impact of different feeding strategies on enteric methane emissions using the Nordic feed evaluation system NorFor. (*manuscript*)

Papers I-IV are reproduced with the permission of the publishers.

The contribution of Maria Henriksson to the papers included in this thesis was as follows:

I Participated in planning the study, collecting data and interpreting results and contributed smaller parts of the manuscript writing.

II Planned the study, performed the data collection, analysed data together with the co-authors and wrote the major part of the paper.

III Planned the study, performed the data collection, analysed the data and wrote the paper.

IV Planned the study, performed the data collection, analysed the data and wrote the major part of the paper.

V Planned the study, performed the data collection, analysed the data and wrote the major part of the manuscript.

Abbreviations and Terminology

CF	Carbon Footprint; the total amount of GHG emissions emitted along the production chain of a defined product.
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent; the standard metric that make different GHGs effect on climate change comparable based on their GWP. 1 kg CO_2e =1 kg CO_2.
DM	Dry matter; the mass of something completely dried.
DMI	Dry matter intake (related to animal feed intake in this thesis)
ECM	Energy corrected milk; milk corrected for fat and protein content to make milk from *e.g.* different herds, comparable.
EF	Emission factor; the average emission rate of a given GHG for a given source, relative to units of activity, *e.g.* amount N_2O/kg N applied to soil.
FU	Functional unit; quantifies the service delivered by the studied system, providing a reference to which the inputs and outputs can be related.
GHG	Greenhouse gas; a gas that effectively absorbs and emits thermal infrared radiation and thus trap heat within the surface-troposphere system.
GWP	Global warming potential; indicate a GHG relative effect on climate change for a fixed time perspective, e.g. 100 years, compared to the same mass of CO_2.
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment; a method used to analyse the environmental impact from the entire life cycle of a product.
LU	Land use; cultivation of arable land.
LUC	Land use change; land transformed from a native state (*e.g.* tropical forests) into agricultural land.
N_2O	Nitrous oxide, 'laughing gas'

1 Introduction

The world faces severe problems with increasing concentrations of greenhouse gases (GHG) in the atmosphere, a situation that is progressively warming the Earth's surface and leading to changes in climate systems, resulting in *e.g.* melting glaciers, extreme weather conditions and rising sea levels. The effects of these changes are already being experienced by people in different parts of the world. It is claimed that human activities contribute substantially to these GHG emissions and that it is very likely that these activities are causing observed change to a warmer climate (IPCC, 2013).

Milk is an important and nutrient-rich food source for humans. Dairy products contribute significantly to the intake of protein and micronutrients in the human diet, especially in developed countries, and have positive effects on human health. Milk production thus constitutes a substantial part of nutrient security for a future world population. As a result of the growing world population and increasing milk consumption *per capita* (mainly in developing countries), the global demand for milk is increasing and it is estimated to rise by 58% during the coming 40 years (van Hooijdonk & Hettinga, 2013; Alexandratos & Bruinsma, 2012; FAO, 2011). Due to this growing demand and the environmental impact of milk production, *e.g.* as regards GHG emissions, it is important that milk can be produced efficiently in a climate-smart way.

The food production sector has been estimated to contribute 19-29% (9.8-16.9 Gt CO_2e in 2008) of total anthropogenic GHG whereof agriculture production constitutes around 90% (Vermeulen *et al.*, 2012). The main contributors are tropical deforestation, methane (CH_4) from livestock and rice cultivation and nitrous oxide (N_2O) from managed soils (Foley *et al.*, 2011). The livestock sector is estimated to produce 14.5% of total anthropogenic GHG and the dairy sector alone is estimated to contribute 2.9%, or 4.3% if meat from milk production is included (Gerber *et al.*, 2013). Approximately one third of the cow's milk in the world (614 Mt) is produced in Europe, but less than 1% of this is produced in Sweden (FAOSTAT, 2013b). However, although Sweden's share of total global milk production is very small, it can be used to represent the many high yielding intensive dairy production systems in Northern and Western Europe.

After the publication of the FAO (Food and Agriculture Organisation of the United Nations) report "*Livestock's Long Shadow*" (Steinfeld *et al.*, 2006) on livestock's contribution to climate change, pressure increased on the dairy and beef sectors to find measures to reduce GHG emissions. By the start of the work described in this thesis, a number of environmental assessments had been performed, stating the magnitude of GHG emissions in different livestock production systems and the different sub-processes with the systems (see *e.g.* review by de Vries and de Boer (2010) and *Table 1*). The production of enteric CH_4 by ruminants has also been studied in depth, mainly focusing on the aspect of increasing milk yield, since the formation of enteric CH_4 also requires part of the animal's energy intake, thus diverting energy from the production of milk. Research in recent years has focused on gaining further insights into the processes and activities that lead to GHG emissions in cattle milk and beef production and how these emissions can be reduced in order to lower the associated impact on climate change. As emissions from the total milk production chain occur before, on and after the farm, the overall emissions need to be studied in a life cycle perspective for the milk product. The life cycle perspective is also important to check that emissions reduced in one part of the chain do not lead to increased emissions in another. Thus, the commonly used methodology in GHG emissions studies is Life Cycle Assessment (LCA) or whole-farm models (Del Prado *et al.*, 2013; Crosson *et al.*, 2011; Schils *et al.*, 2007). GHG estimates for the life cycle of milk have been produced for global (e.g. Gerber *et al.*, 2010), national (e.g. Lesschen *et al.*, 2011) and farm level (see further section 2.5). Important aspects to date have been to identify intensity and hotspots of emissions, define regional variations, compare production systems (*e.g.* intensive versus extensive) and evaluate mitigation measures. The large variation in milk production systems in the world, as well as in climate- and geography-defined production conditions, indicates that mitigation measures will also need to differ depending on the location of dairy farms. Thus, GHG estimates for milk need to be studied on a regional basis in order to evaluate the most effective mitigation measures.

This thesis makes a contribution to the knowledge on GHG estimates for milk, also referred to as milk carbon footprint (CF). In a general perspective, it examines the uncertainties associated with GHG estimates of milk due to due to difficulties in predicting these. In a specific perspective, it examines the variation in GHG emissions between Swedish dairy farms and how feeding strategies influence these emissions.

1.1 Aims and structure of the thesis

The overall aim of this thesis was to add to current knowledge on GHG emissions from Swedish milk production systems, with the focus on management measures for efficient and climate-smart milk production.

Due to the uncertainties associated with estimates of biogenic GHG emissions, the first specific objective was to analyse how emissions factors (EF) used in estimates of N_2O emissions from soil and enteric CH_4 emissions and the most important input data influence the results of GHG estimates of milk. This step was important in determining the relevance of different GHG sources included in the system and in interpreting GHG estimates for milk (Paper I).

The next objective was to map the variation in the most important input variables identified in Paper I for milk production in Sweden, in order to simulate the expected variation in estimated GHG emissions between Swedish dairy farms (Paper II). This provided an indication of the approximate magnitude of the potential to reduce GHG emissions from Swedish milk production.

As enteric CH_4 and feed production contributed more than 85% of the total estimated GHG in Paper I, the next objective was to analyse the effect on these emissions caused by differences in feeding strategy (Papers III-V). Special emphasis was given to GHG emissions from the production of grass/clover silage, as this constitutes the main part of the animals' diet (Paper III). This was intended to provide deeper knowledge and understanding of the impact that feed production and the composition of animal feed rations can have on total GHG emissions from milk production (Papers IV and V).

2 Greenhouse gases and milk production

Greenhouse gases are gases in the atmosphere that effectively absorb and emit thermal infrared radiation and trap heat within the surface-troposphere system. These are primarily water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone. This so called greenhouse gas effect is essential for life on earth but with increased concentration of GHG in the atmosphere the global temperature is increasing which cause changes in the climate. The global livestock sector are estimated to contribute to the anthropogenic GHG emissions with 5% of the CO_2 emissions, 44% of the CH_4 emission and 53% of the N_2O emission (IPCC, 2007a). These emissions have increased annually by 0.7% from 1990 to 2010, with an acceleration during recent years (FAOSTAT, 2013a), presumably owing to the increasing world population.

2.1 Climate change and livestock production

Greenhouse gas emissions from agriculture contribute a significant part of the increasing GHG concentrations in the atmosphere and overall livestock production is estimated to account for 14.5% of total anthropogenic GHG, corresponding to 7.1 Gt CO_2e, including emissions from land use change (LUC) for pasture and soybean production. Almost two-thirds of these GHG emissions are represented by cattle, approximately equally shared between beef and dairy cattle, with the majority estimated to occur in developing regions (Gerber *et al.*, 2013). GHG emissions from livestock production in Sweden in 2005 were estimated to be 7.3 Mt CO_2e (LUC not included) by Cederberg *et al.* (2013a). The complex nature of biological systems and processes makes it difficult to predict biogenic GHG emissions and combined with difficulties in collecting production data (*e.g.* animal numbers and yields), leads to a wide range of uncertainty in assessments of GHG emissions from agricultural production (Gerber *et al.*, 2013; IPCC, 2007a)

In contrast to the energy and industry sectors, where fossil carbon dioxide (CO_2) is the dominant GHG, agricultural production is dominated by emissions from biological processes, *i.e.* methane (CH_4) and nitrous oxide (N_2O). Feed production and CH_4 emissions from enteric fermentation (*i.e.* ruminant feed digestion) contribute the largest proportion of emissions from agriculture and 9% of the emissions are referred to as biogenic CO_2 emissions from LUC, *i.e.* transformation of native land to pasture or arable land (Gerber *et al.*, 2013). The contributions of GHG emissions from various activities are illustrated in Figure 1.

Global cattle milk production contributes approximately 20% of total livestock emissions (i.e. 1.4 Gt CO_2e not including production of meat) (Gerber *et al.*, 2013). The CH_4 from enteric fermentation dominates the emissions, especially where the productivity is low, whereas emissions from feed production in general contribute a larger share where the productivity is high (*e.g.* W Europe) (*Figure 1*). Relating GHG emissions to animal productivity, there is a large variation between regions and dairy systems. The lowest emissions per unit of milk are found in industrialised regions (<1.7 kg CO_2e/kg milk) with high productivity due to good feed availability and quality. The highest emissions per unit of milk are found in countries in Sub-Saharan Africa (up to 9 kg CO_2e/kg milk), where animal productivity is very low and cattle are also kept for other services, *e.g.* draught power (Gerber *et al.*, 2013; Gerber *et al.*, 2010).

2.2 Sources of greenhouse gas emissions

2.2.1 Nitrous oxide

Nitrous oxide is the most potent of the agricultural GHG, with an effect 298 times that of CO_2, and its estimates are also associated with the largest uncertainty. The majority of the N_2O is produced in soil (caused by applying nitrogen (N) fertiliser), but significant shares also originate from production of synthetic N-fertilisers and manure (see below) and indirectly from volatised ammonia (NH_3) (primarily derived from manure) (*Figure 1* and *6*). N_2O is produced when N compounds in manure, mineral fertiliser, plant residues or other organic matter are decomposed and mineralised under certain conditions, as illustrated in *Figure 2*.

N_2O production in soil is carried out by a large community of different bacterial species involved in mineralisation of N compounds in the soil.

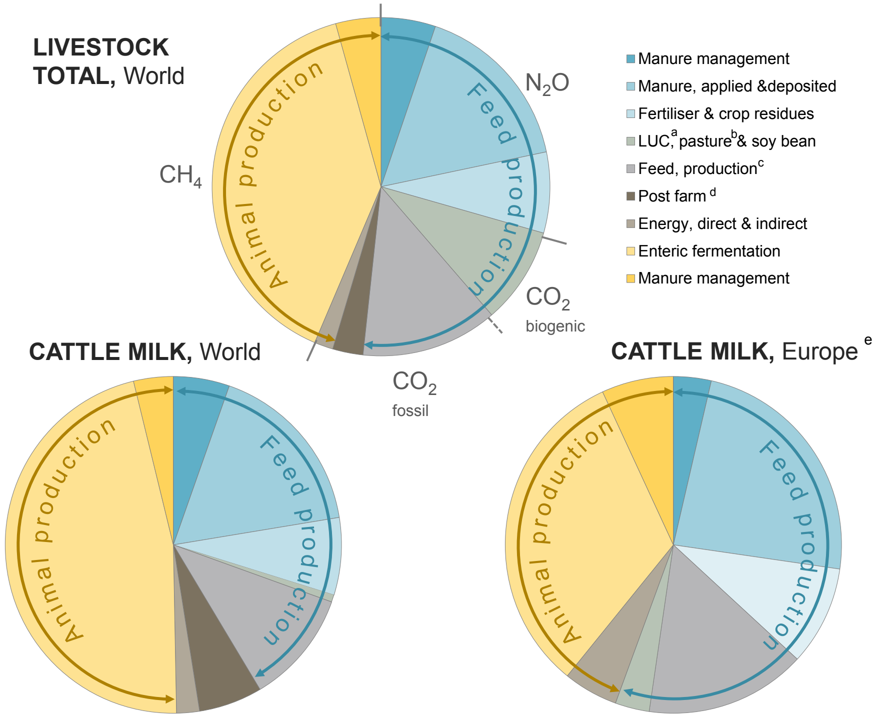

Figure 1. Main sources of global emissions from world livestock (above) and cattle milk production (left), and from cattle milk from West Europe (right) (from Gerber *et al.*, 2013). [a]Land use change, [b]for livestock, [c]includes processing and transport, [d]CO_2 from processing and transport of animal products, [e]does not include post-farm CO_2.

Depending on the availability of oxygen (O_2), the process is defined as either nitrification (aerobic process) or denitrification (anaerobic conditions). Denitrification is generally regarded as the most important source of N_2O emissions (Wrage *et al.*, 2004), but nitrification can also make significant local contributions to the overall emissions (Kavdir *et al.*, 2008) (*Figure 2*). The most favourable soil conditions for N_2O production seem to arise when 65-85% of the pore space is filled with water (Flechard *et al.*, 2007), there is high availability of nitrate (NO_3^-) and nitrite (NO_2^-), and easily available carbon (C) is present as 'food' for the denitrifying bacteria. Thus, important soil management practices that influence the production of N_2O are application time and rate of N, soil acidity (low pH increases emissions), soil structure and water drainage (soil compaction and poor drainage increase anaerobic conditions and thus denitrification) (Singurindy *et al.*, 2009; Hofstra & Bouwman, 2005; Kaiser *et al.*, 1998).

There is a huge variation and complexity in the function and composition of microbial and bacterial communities in soil, which also vary spatially in fields due to differences in chemical and physical properties of the soil. Combined with seasonal and annual variations in meteorological conditions and cultivation practices, this makes N_2O emissions difficult to predict and thus associated with great uncertainties in GHG estimates.

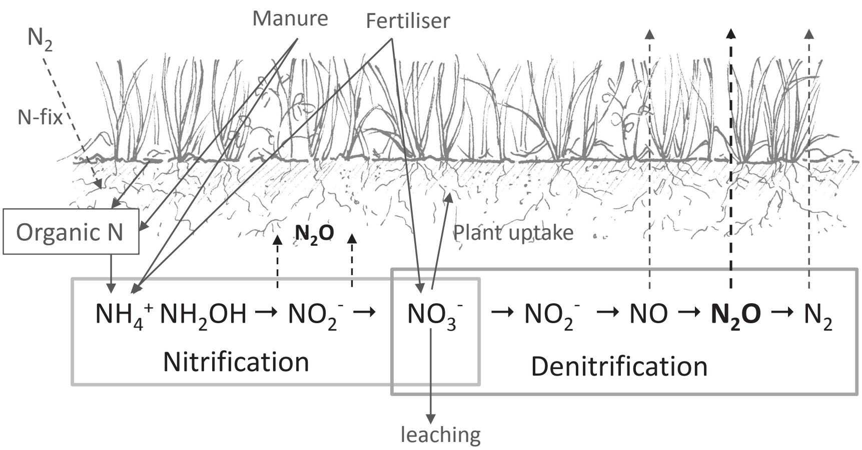

Figure 2. Illustration of nitrogen (N) flows in soils and the production of nitrous oxide (N_2O).

In manure, N_2O is produced under O_2-limited conditions by the same processes as in soil. Favourable conditions for N_2O production are found especially in stored deep litter, but also in stored solid manure and in the surface crust formed on stored and spread slurry and on faeces dropped during grazing (Petersen *et al.*, 2013). In the context of GHG estimates of Swedish milk, these emissions make a minor contribution, as the majority of the manure is managed as slurry and the grazing period is comparatively short. N_2O emissions in cow houses with liquid manure systems are very low (Ngwabie, 2009).

N_2O emissions from fertiliser plants are caused by limited refinement of N_2O in the production of ammonium nitrate (NH_4NO_3), which comprises the majority of the N-fertiliser used in Sweden. Technology to reduce these emissions is available, but not yet generally in use at fertiliser plants. For Sweden it can be assumed that 60% of N-fertiliser is produced with the best available technology (BAT) to reduce N_2O emissions. Since N-fertiliser production is an industrial process, these N_2O emissions can be estimated with high certainty.

2.2.2 Methane

The main CH_4 emissions in dairy production are from enteric fermentation, where CH_4 is produced as a by-product in the rumen and large intestine of the animals, as illustrated in *Figure 3*. This is a process developed over millennia to allow ruminants to digest cellulose. When billions of microbes digest the feed in the anaerobic environment of the rumen, cellulose is decomposed into volatile fatty acids (acetate, propionate and butyrate), hydrogen (H_2) and CO_2. The high acidity that the H_2 released could induce is avoided by the methanogenesis process, performed by number of different methanogen species which use H_2 and CO_2 as substrates to form CH_4 (*Figure 3*). The amount of enteric CH_4 produced depends on feed intake, the structure and nutrient composition of the feed and other animal parameters (*e.g.* productivity and breed). Individual variations in CH_4 production not related to feed or productivity have been found and can be partly explained by variations in rumen microbial communities. (Cieslak *et al.*, 2013; Ramin, 2013; Johnson & Johnson, 1995).

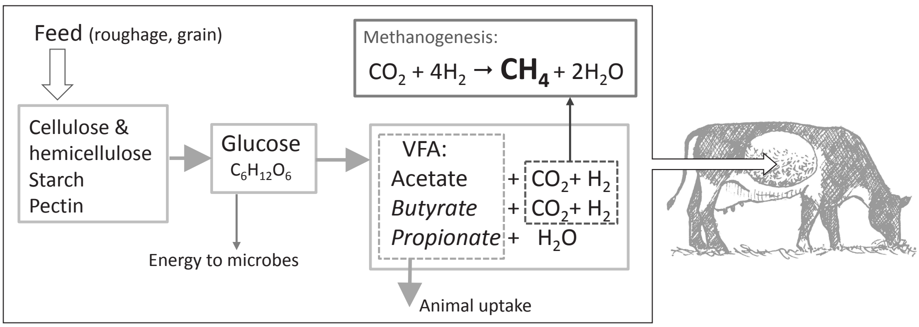

Figure 3. Schematic illustration of methane (CH_4) production in the rumen. VFA =Volatile fatty acids.

A consequence of enteric CH_4 formation is that around 6.5% of the animal's gross energy intake is lost (IPCC, 2006a). This has prompted a great range of research to identify dietary strategies that reduce the formation of CH_4 without lowering animal productivity. The most promising alternatives appear to be addition of fats, diets with increased starch content and use of some feed additives (Grainger & Beauchemin, 2011). Forage is generally associated with increased production of enteric CH_4 (Johnson & Johnson, 1995), but forage digestibility is a parameter that can reduce this increase (Brask *et al.*, 2013; Patel *et al.*, 2011).

CH_4 is also produced in excreta and manure and emitted in animal houses and during storage. It is formed from the undigested organic matter that remains in the excreta by the same processes and under similar anaerobic conditions as in the rumen. The surface crust that is normally found on stored cattle slurry prevents CH_4 emissions due to the presence of O_2 (in contrast to the case for N_2O). For the same reason, emissions of CH_4 from deep litter and solid manure are low (Petersen *et al.*, 2013).

2.2.3 Carbon dioxide

Fossil CO_2

CO_2 is emitted when various types of fossil fuels are combusted for energy purposes. Energy is used in various processes/activities on the farm (*e.g.* milking, grain drying and field operations), as well as in industrial processes (*e.g.* mineral fertiliser and feed production) and in transport. The CO_2 emissions from combustion of fossil fuel can be estimated with high certainty using accurate data on fuel type and amounts used.

Biogenic CO_2

CO_2 is also emitted from decomposition of organic matter and respiration of animals. The short-term C cycle, including CO_2 assimilated and emitted by plants, animals and manure, can be assumed to be carbon-neutral, as the CO_2 is re-released quickly in the C cycle, and is thus generally not included in LCA (IDF, 2010). In a GHG estimate for milk, Rotz *et al.* (2010) included CO_2 assimilated in feed (in North America) and estimated the net balance to have a reducing effect on milk CF.

CO_2 emissions can also be released from long-term stored C in soil and vegetation and thus contribute as a net source of CO_2 to the atmosphere. These emissions are associated with direct LUC, *i.e.* when land is transformed from native state (*e.g.* tropical forests and *cerrado*) into agricultural land by deforestation and soil cultivation, or from land use (LU) when crop cultivation strategy changes (*e.g.* from perennial to annual crops). Climate conditions, soil texture, oxidation time for soil organic matter and initial amounts of soil organic carbon (SOC) are some factors with a large impact on the amount of net released CO_2 (Bolinder *et al.*, 2010; Johnston *et al.*, 2009). The process of soil CO_2 emissions and C sequestration is reversed over time, unlike for the other biogenic GHG (CH_4 and N_2O), since emitted CO_2 is returned to soil as C through photosynthesis. Changes in CO_2 emissions from LUC and LU are difficult to calculate due to the nature of decomposition, but also due to choice of method and input data, and thus uncertain (Cederberg *et al.*, 2013b).

2.3 Milk production in Sweden

Milk production in Sweden is intensive and highly specialised, with an average milk yield slightly above 9000 kg energy corrected milk (ECM) from Swedish Holstein (50%) and Swedish Red and White Breed (40%). Today almost 5000 farms deliver 2.86 Mt milk from 348 000 cows. Half these dairy cows are found in the southern Swedish counties of Västra Götaland, Kalmar, Skåne and Halland. There has been a constant decrease in number of cows and dairy farms over recent years. For example, from 1998 to 2012, the number of dairy farms decreased by 67%, the number of dairy cows by 23% and the amount of milk delivered by approximately 15%, which denotes the trend in the sector for increased milk yield per cow (average 1.3% per year) and increased herd size to on average 70 cows/production unit (with approximately 40% of the total number of cows in herds with more than 100 cows). Average values and variations in some production data from 1050 dairy farms in 2005 are shown in Table 5. The data for the table were obtained from the official Swedish milk recording system, which provides comprehensive statistics on national milk production as it comprises around 85% of Swedish dairy cows.

The animals are kept indoors most of the year in loose or tie-stall houses and manure is generally managed as slurry and removed daily to outdoor storage units. The average calving interval is 13.3 months, the age at first calving is 28 months and replacement rate is on average 38% (*i.e.* cows annually replaced by heifers). Specialist dairy farms commonly keep heifer calves for replacement and sell bull calves to be raised to about 20 months at slaughter on specialist beef farms. Cows are culled for slaughter at about 5 years of age (*i.e.* 2.4 lactation periods). The animals are fed roughage, grain and concentrate. Grass and clover silage dominate the diet, comprising on average around 50% for cows and around 80% for heifers (Cederberg *et al.*, 2009b), on some farms complemented with forage maize (where conditions permit its cultivation).

Roughage and some grain are normally grown on the dairy farms, while protein concentrates are purchased. Domestic crops for protein include rapeseed (the by-product rapeseed meal) and horse bean, to supplement the main protein intake from grass and clover silage. Another protein feed is the by-product dried distiller's grain from national ethanol production. Due to the Nordic climate, feed intake from grazing is limited to approximately three summer months, or some months longer for heifers, but with the increase in farm size it has become more common to keep cows outdoors mainly for exercise (national animal welfare regulations require a certain outdoor period), combined with indoor feeding throughout the year.

The majority of feedstuffs used on dairy farms can be produced in Sweden, but variations in length of the growing season (decreases with latitude from 55ºN to 66ºN) and weather conditions limit the productivity of species in some regions. Due to this and depending on market prices, there are also significant imports of protein feed, especially soymeal and rapeseed meal. Soy meal is imported from Brazil due to national agreements in the dairy industry to use GMO-free feed. Other by-products from the cereal and sugar industry are also used in dairy feeds.

2.4 The life cycle of milk production

The life cycle of a product can be defined as the production chain that starts with the extraction and refinement of raw materials (the so-called cradle) and ends with the disposal and waste management of the packaging (the so-called grave), which in other words means inclusion of activities that happen prior to and after the activities performed on the dairy farm. However, >90% (globally) of GHG emitted from the life cycle of milk occur pre-farm gate and a common analytical strategy is thus to separate the milk life cycle into pre- and post-farm gate processes and activities (Gerber *et al.*, 2010). This is also commonly done in analysis of GHG emissions from agricultural products, which often end at the 'farm gate'. In this thesis, the pre-farm gate part, until milk leaves the farm, was assessed, as illustrated in *Figure 4* and *5*.

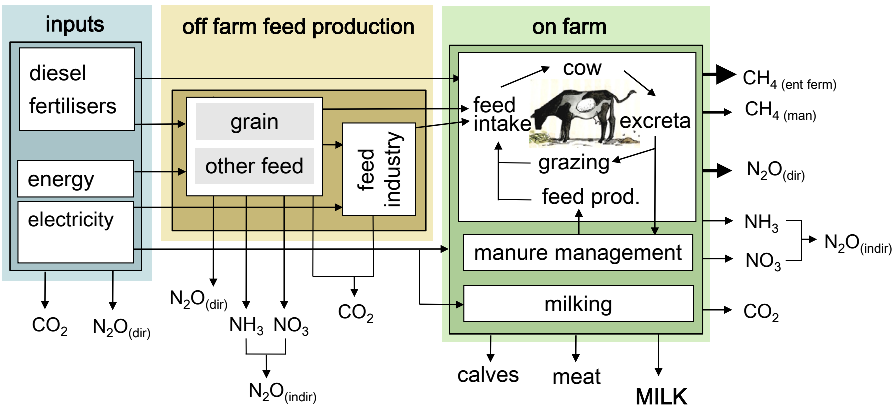

Figure 4. Flowchart of milk production in Sweden from cradle to farm gate, with emissions of fossil carbon dioxide (CO_2), direct and indirect nitrous oxide (N_2O), methane from enteric fermentation and manure (CH_4), ammonia (NH_3) and nitrate (NO_3^-). CO_2 emissions from soil and carbon sequestration are excluded.

Although milk is the main product from the milk production system, there are also the by-products of surplus calves, meat from culled cows and manure. However, manure can be assumed to circulate within the system and not constitute an output, as was done in this thesis. Even though milk and beef production have been separated into two specialist production systems with different cattle breeds for milk and beef, respectively (although dual purpose breeds also exist), they are closely connected in that meat is an outcome from the milk production system too. For example, if the meat output from the milk production system decreases due to a decreasing number of dairy cows, it has to be produced in a parallel beef production system (Zehetmeier *et al.*, 2012; Flysjö *et al.*, 2011a). This is an important aspect when assessing GHG emissions from milk and meat production and when comparing or simulating system changes, since the emissions per unit meat are larger from the pure beef production system than from the milk production system. However, this issue is not considered in the present thesis, which only analyses changes within the milk production system that do not change the product outcome of the system. Nevertheless, the issue is discussed in more detail in section 5.2.1.

2.5 Studies of GHG emissions from milk production

Several studies on the impact of milk production on climate change have been performed using LCA methodology or specially developed whole farm models, which have contributed much knowledge on how GHG emissions are associated with the production of milk (*Table 1*). Important aspects in these studies have been identification of hotspots of emissions and of the parameters and variables most influencing the emissions and comparisons of different production systems, resulting in possible mitigations to reduce GHG emissions. Emissions of GHG from Swedish dairy systems have been assessed in a number of previous studies that have used different approaches such as bottom-up and top-down calculations to compare system intensity and organic and conventional milk production (*Table 1*).

Since methodology can be expected to differ between studies (*e.g.* system boundaries, GHG prediction models and allocation methods), it is not recommended that results from different studies be compared without knowledge of the methodology used (see Paper I and discussion section).

Table 1. *Greenhouse gas estimates of milk at farm gate according to a selection of previous studies. Note that expected differences in methodological choices (i.e. system boundaries, allocation, GHG prediction models) make direct comparisons uncertain. (ECM=energy corrected milk, FCPM= fat and protein corrected milk)*

System studied	Unit	kg CO_2e	Country	Reference
Swedish average	1 kg ECM	1.16	SE	Present thesis
Swedish average, top down	1 kg ECM	1.02	SE	Cederberg *et al.* (2013a)
Single farms conventional (n=16)	1 kg ECM	1.01	North SE	Cederberg *et al.* (2007)
Single farms organic (n=7)	1 kg ECM	0.93	North SE	Cederberg *et al.* (2007)
Single farms >7500 ECM/ha (n=9)	1 kg ECM	0.89	S West SE	Cederberg and Flysjö (2004)
Single farms <7500 ECM/ha (n=8)	1 kg ECM	1.04	S West SE	Cederberg and Flysjö (2004)
Single farms organic (n=6)	1 kg ECM	0.94	S West SE	Cederberg and Flysjö (2004)
Single farms conventional (n=35)	1 kg ECM	1.06	DK	Kristensen *et al.* (2011)
Single farms organic (n=32)	1 kg ECM	1.10	DK	Kristensen *et al.* (2011)
Norway average, 3 dairy regions	1 kg ECM	1.53	N	Roer *et al.* (2013)
Average western France conv.	1 kg FCPM	1.04	France	van der Werf (2009)
Average Irish dairy units	1 kg ECM	1.3	I	Casey and Holden (2005)
Conventional single farms (n=10)	1 kg FPCM	1.4	NL	Thomassen *et al.* (2008)
Conventional	1 l milk	1.06	UK	Williams *et al.* (2006)
Intensive (n=6)	1 kg milk	1.3	G	Haas *et al.* (2001)
Average, eastern Canada	1 kg FCPM	0.92	Canada	Mc Geough *et al.* (2012)
Average, California and Wisconsin	1 kg milk	1.09	USA	Phetteplace *et al.* (2001)
Average, California farms	1 kg ECM	0.57	USA	Rotz *et al.* (2010)
New Zealand average	1 kg milk	0.93	NZ	Basset-Mens *et al.* (2009b)

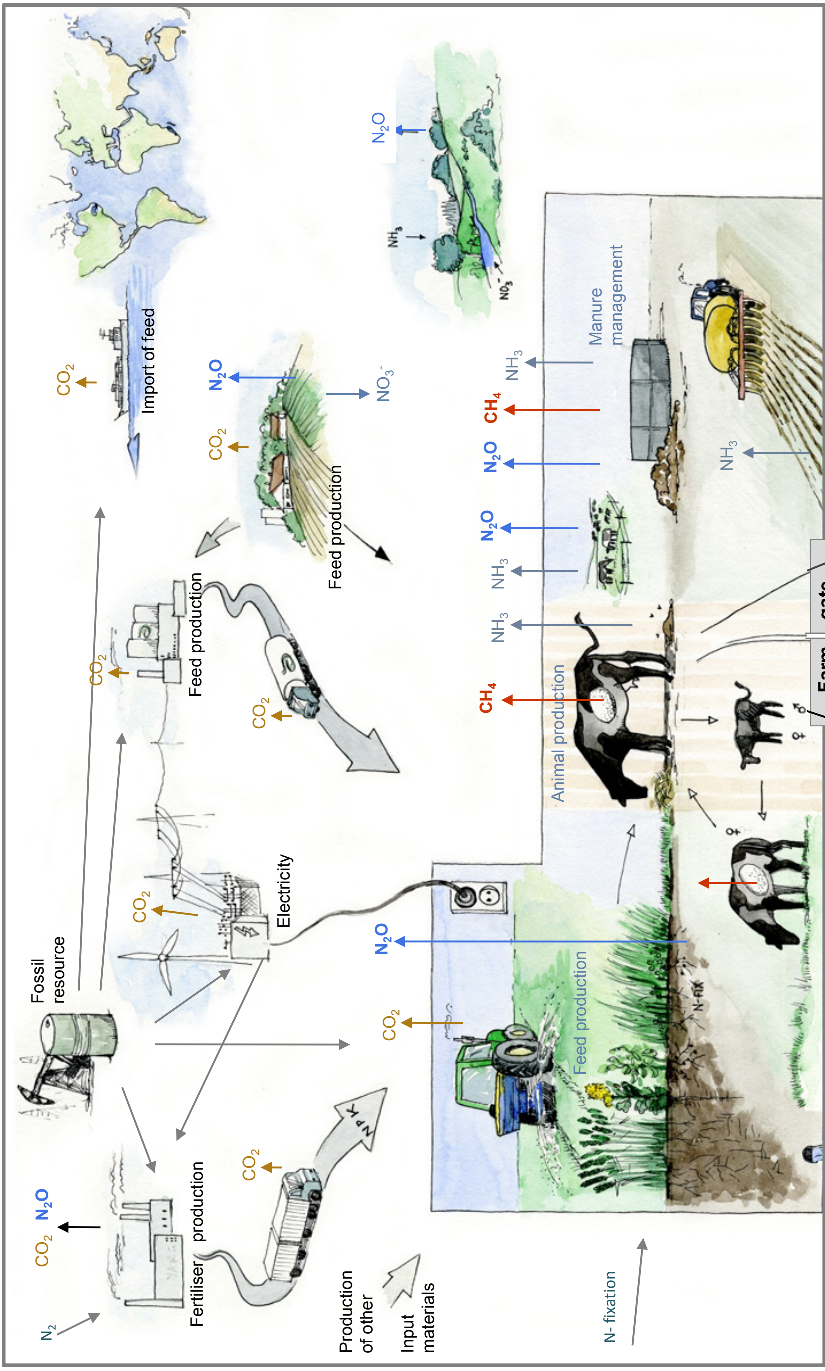

Figure 5. Illustration of the milk production chain from cradle to farm gate, showing the sources of emissions of the greenhouse gases carbon dioxide (CO_2) (fossil), nitrous oxide (N_2O) and methane (CH_4), as well as ammonia (NH_3) and nitrate (NO_3^-) causing indirect emissions of N_2O.

3 Methods

3.1 Systems analysis (Papers I-V)

The systems analysis used here for estimating GHG emissions followed the standardised methodology of Life Cycle Assessment (ISO, 2006a; ISO, 2006b). This method is generally used to analyse the environmental impact (*e.g.* contribution to global warming, eutrophication and acidification) from the entire life cycle of a product, *i.e.* from 'cradle to grave', including all resources used and all emissions to air, soil and water. The LCA of a product's impact solely on global warming is commonly referred to as that product's carbon footprint (CF).

Average data were used to assess the emissions from the processes and activities included in the production chain (also defined as an 'attributional' LCA), as recommended in the International Dairy Federation guidelines on standard LCA methodology for the dairy industry (IDF, 2010). This means that any indirect effects that changes in the outcome from the milk production system can have on other production systems (*e.g.* meat production) are not considered in this thesis.

The GHG emissions from the different processes within the production chain of milk were calculated using the various prediction models and emissions factors described in section 3.2. These calculations were mainly carried out with the LCA software tool SimaPro7 (PRé Consultants, 2010).

Functional unit

The functional units (FU) used in this thesis, *i.e.* the units that describe the specified function of the system studied and the reference base to which all emissions are related (distributed across), are summarised in *Table 2*. The FU used differed depending on the system studied. Papers I and II studied the total milk production system, while Papers III and IV studied GHG emissions occurring only from feed production and Paper V only CH_4 emissions from enteric fermentation. Milk yield was standardised to energy corrected milk (ECM) (*i.e* corrected for fat and protein content) according to (Sjaunja *et al.*, 1990).

Table 2. *Functional units (FU) and system boundaries for systems within Swedish milk production studied in this thesis. All FU include by-products from the system.*

System studied	Functional unit	System boundary	Studied in
Milk production	1 kg energy corrected milk (ECM) delivered at farm gate	Cradle to farm gate	Paper I Paper II
Silage production	1 kg dry matter intake (DMI) of grass/clover silage	Cradle to feed consumed (including construction of bunker silo and feed losses)	Paper III
Feed ration production	1 kg ECM from a cow with an annual milk yield of 9900 kg ECM	Cradle to feed consumed (including replacement animals, emissions from manure application and excreta on pasture and feed losses)	Paper IV
Feedstuff production	1 kg dry matter (DM) of single feedstuff	Cradle to feed produced on farm or delivered at feed industry	Paper IV
Enteric methane production	1 kg ECM produced from a cow with an annual milk yield of 8900, 9900 and 10900 kg ECM respectively	Feed intake to feed digested	Paper V

System boundaries

System boundaries define what is included and not in the system under study. These are for present thesis summarised in *Table 2*. The systems studied included all inputs from ‘cradle’ to ‘farm gate’ (Papers I and II) or ‘cradle’ to ‘feed consumed’ (Papers III and IV), traced back to the extraction of raw materials used and all outputs of N_2O, CH_4 and fossil CO_2 emissions from the system were accounted for (*Table 2* and *Figure 4*). However, some minor sources of emissions were left out, *e.g.* production of pesticides, detergents and medicines. Emissions associated with capital goods (*e.g.* manufacturing of machinery and construction of buildings) were included only for energy and transport, since capital goods are known to have a small impact on the GHG emissions from milk production (Frischknecht *et al.*, 2007) and were assumed to be constant. Only heifer calves used for replacement were included in the system.

Biogenic CO_2 released and restored as C in cultivated soils and grassland was not included, since this process was assumed to be in equilibrium. CO_2

emissions related to LUC were only included in a sensitivity analysis for soy meal (Paper IV), due to the very high uncertainty associated with these emissions (as further discussed in section 5.1.2).

Allocations

No allocations of GHG emissions were made between milk and by-products obtained from the production systems (*e.g.* surplus animals and meat from culled cows), as the primary aim of the studies performed was to analyse the impact from various parameters, variations and uncertainties, and not to perform a final milk CF. All manure was assumed to be used in feed crop cultivation and straw was assumed to be returned to soil as plant residues or in manure.

Allocation in the feed production system, *i.e.* when the cultivated crop results in more than one product, was based on the economic value of the products. For example, rapeseed and soybean produce both oil and meal and crops cultivated for *e.g.* wheat flour, sugar and ethanol also result in the by-products grain bran, dried beet pulp and distiller's dried grain, respectively, which are products used for feed.

3.2 Prediction models and emissions factors for GHG emissions

To be comparable, estimated GHG were converted to carbon dioxide equivalents (CO_2e) based on their global warming potential (GWP) in a 100-year time horizon according to IPCC (2007b), *i.e.* with the conversion factors 1 for CO_2, 25 for CH_4 and 298 for N_2O and the units kg CO_2e/kg GHG.

3.2.1 Nitrous oxide

Soil

Direct emissions of N_2O from soil were calculated as a direct function of the amount of N applied to the soil as synthetic fertiliser, manure and plant residues above and below ground. The emissions factors (EF) used are summarised in *Table 3*. Indirect N_2O emissions from soil caused by volatisation of NH_3 and leached NO_3^- were based on calculated NH_3 emissions from excreta (indoor and on pasture) and manure (storage and spreading) according to Karlsson and Rodhe (2002) and leached NO_3^- according to Aronsson and Torstensson (2004), taking into account variations in spreading time and techniques, soil types and climate conditions, as further described in Papers I-IV. NH_3 emissions from mineral fertiliser (*i.e.* NH_4NO_3) were taken to be 0.02 kg NH_3-N/kg N applied (Hutchings *et al.*, 2001).

Table 3. *Emissions factors (EF) for nitrous oxide (N_2O) used in this thesis*

Emissions source	Emissions factor, EF	Reference
N_2O_{direct} from soil[a]	0.01 kg N_2O-N/kg applied N	IPCC (2006b)
N_2O_{direct} from pasture	0.01 kg N_2O-N/kg N in excreta	Kelliher *et al.* (2005)
N_2O_{direct} from pasture[b] (paper IV)	0.02 kg N_2O-N/kg N in excreta	IPCC (2006b)
$N_2O_{indirect}$ from volatised NH_3	0.01 kg N_2O-N/kg NH_3-N	IPCC (2006b)
$N_2O_{indirect}$ from leached NO_3^-	0.0075 kg N_2O-N/kg NO_3^--N	IPCC (2006b)

[a] Includes N in excreta on pasture
[b] Pasture on grassland in crop rotation

Manure

N_2O emissions from the storage of manure were calculated based on N in excreta and an EF of 0.005 kg N_2O-N/kg N excreted for slurry and solid manure and 0.01 kg N_2O-N/kg N for deep litter (IPCC, 2006a).

Fertiliser production

In Papers I and II, GHG emissions from the production of N-fertiliser (ammonium nitrate, NH_4NO_3) were set to 6.8 kg CO_2e/kg N (two thirds from N_2O), representing the emissions from European average fertiliser plants (Jenssen & Kongshaug, 2003). In Papers III and IV, the emissions were set to 5.27 kg CO_2e/kg N (60% from N_2O) as used in Wallman *et al.* (2011), representing a mix of ammonium nitrate produced in fertiliser plants with BAT to reduce N_2O emissions (60%) and the European average fertiliser plant (40%), which was the situation assumed for synthetic N-fertiliser used in Sweden.

3.2.2 Methane

Enteric fermentation

Estimates of enteric CH_4 were based on the empirical prediction models and EF values summarised in *Table 4*. Another five models developed by Yan *et al.* (2000), Mills *et al.* (2003) and Jentsch *et al.* (2007) were used in a sensitivity analysis and are further described in Paper V.

Manure

CH_4 emissions from stored manure and excreta deposited on pasture were calculated following the Tier 2 method in IPCC guidelines (IPCC, 2006a). However a national methane conversion factor (MCF) of 4% based on *in vivo* measurements by Rodhe *et al.* (2009) was used for slurry instead of the 10% proposed by IPCC.

Table 4. *Methods for estimating enteric methane used in this thesis*

	Equation or emission factor (EF)	Referens
Paper I	EF: 21.6 g CH_4/kg dry matter intake	Clark (2001)
Paper II	EF_{cow} (kg CH_4/head and year) = (DE * MCR / 55.65) * 365 DE=digestible energy (MJ/head*day) MCR=methane conversion rate	Bertilsson (2001), Lindgren (1980) and Naturvårdsverket (2009)
Paper II	Heifers: 53 kg CH_4/head	Cederberg *et al.* (2009b)
Paper V	Cows: CH_4 (MJ/day)=2.87+1.23*DMI-0.1164*FA DMI=dry matter intake (kg/day) FA=fatty acids (g/kg DM)	Nielsen *et al.* (2013)
Paper V	Heifers: CH_4 (MJ/day)=(-0.046*conc_share+7.1379)/100*GE Conc_share= concentrate share (%) GE=gross energy intake (MJ/day)	Nielsen *et al.* (2013)

3.2.3 Carbon dioxide

Fossil

Emissions from the production of energy and fuel and from the combustion of fuel were calculated based on the Ecoinvent database (Ecoinvent, 2010), which is incorporated into the LCA software tool SimaPro.

Biogenic

In the sensitivity analysis, emissions from LUC associated with Brazilian soy bean production were calculated with two LUC factors for soy meal, as reported Gerber *et al.* (2010) and Leip *et al.* (2010). These were 7.38 and 2.78 kg CO_2e/kg soy meal, respectively, when delivered to Swedish feed industries (Paper IV).

3.3 Acquisition of input data

Input data were taken from national statistics (Swedish Board of Agriculture, 2011b) to define *e.g.* crop yields, manure management, number of animals *etc.* The national milk recording system provided current herd performance data, *e.g.* replacement rate, lactation periods, age at first calving *etc.* (Swedish Dairy Association, 2011). Farm-specific milk production data were taken from a national database where production data collected in the advisory services programme '*IndividRam*' are stored (currently administered by the farm-owned dairy advisory services company Växa Sverige, www.vxa.se) (Paper II). Farm-specific data on nutrient balances were taken from a national database run by the Swedish Board of Agriculture (www.greppa.nu).

The most important national reports that provided data on Swedish average milk production were Cederberg *et al.* (2009b) (Papers I and II), Flysjö *et al.* (2008) while Wallman *et al.* (2011) and the LCA-data base at the Swedish Institute for Food and Biotechnology (SIK) was used for data to estimate GHG emissions from feed production and Swedish Board of Agriculture (2009) for data on cultivation application rates of N, phosphorus and potassium. Expert knowledge from the dominant national advisory services companies, Växa Sverige (www.vxa.se) and the Swedish Rural Economy and Agricultural Societies (Hushållningssällskapet, www.hushallningssallskapet.se), was also an important source of information relating to feed rations and crop production.

3.4 Modelling feed rations and dairy herds

The feed rations used in Papers III-V were optimised using the semi-mechanistic, static and science-based feed evaluation model NorFor, which includes economic optimisation and is commonly used in Sweden, Denmark and Norway (Volden, 2011; Weisbjerg, 2010). The optimisation was carried out by experienced feed advisors from regional advisory services according to predetermined characteristics for the rations and pre-defined optimisation settings in the model.

All rations represented a total herd ration that was allocated to an average dairy cow with a predefined annual yield of ECM, including the replacement heifer. The rations were based on an average Swedish Holstein herd with 334 days lactation period, 74 days dry period, 13.4 months calving interval, 28.2 months age at first calving and 38% replacement rate. The average herd rations were aggregated from daily rations for the different animal categories (*e.g.* animals in different lactation stages, dry periods or growth phases), as well as indoor and grazing periods (further described in Paper IV).

A general dairy herd of 120 lactating cows (of which 46 were first calvers) was modelled in order to estimate land requirements and amounts of available manure for crop production and synthetic N-fertiliser rates as these are affected by manure availability. Data on nutrients in excreta from each ration were obtained from NorFor. A loose-housing system with manure handled as slurry was assumed and the allocation of excreta between house and pasture was made according to each region's grazing ration and period.

With a 38% replacement rate the herd would consist of 0.89 heifers per cow, equal to 46 heifers <12 months and 67 heifers 12-28 months, based on the average herd performing data above. A late discovered error (i.e. too late to be corrected) revealed that the calculations in Paper IV, which were based on 0.98 heifers per cow (50 replacement heifers <12 months and 67 heifers 12-28 months), instead equalled the total number of heifers in the herd, or a replacement rate of 42%. This means that all results in Paper IV are approximately 2% higher than if calculated for a 38% replacement rate. Paper V was calculated with the correct number of heifers for a 38% replacement rate.

3.5 Sensitivity analysis

3.5.1 Monte Carlo analysis

Uncertainty in milk CF related to emissions of N_2O from soil and CH_4 from enteric fermentation (Paper I) was analysed with a Monte Carlo simulation (performed with the LCA software SimaPro7, PRé Consultants (2010)). The same methodology was used to analyse the variation in milk CF between Swedish dairy farms due to management differences (Paper II). The Monte Carlo simulation was operated by randomly choosing one value within the uncertainty range for each EF (Paper I) for 5000 iterations of milk CF estimates. In Paper II, values were randomly chosen from the variation range of each defined production parameter. The uncertainty and variation ranges were defined by standard deviations and whether the values were normally or log-normally distributed. Due to the numerous iterations, an uncertainty range in GHG estimates of milk caused by uncertainty in prediction of soil N_2O and enteric CH_4 was calculated, as well as a range of variation due to management differences.

3.5.2 Other sensitivity analysis

The impact of individual parameters on GHG estimates of milk was analysed by increasing the value of one parameter at a time and observing changes in the overall milk CF and in the different GHG (*Figure 7*) (Paper I).

The influence of crop yield on GHG emissions and the land requirement for feed production was analysed by varying crop yield by ±10% (annual crops) and ±20% (grass) (including modification of manure application rates and thus N-fertiliser rates, caused by the change in land requirement when yields were changed) (Papers III and IV). The influence of feed losses from grass silage storage and feeding was similarly analysed by halving losses from storage and excluding or increasing losses from feeding.

The effect of biogenic CO_2 emissions from LUC (*i.e.* associated with soybean production) on GHG estimates for different feed rations was analysed by using two different LUC factors for soy meal, as described in section 2.2.3 (Paper IV).

The uncertainty in predicting enteric CH_4 was assessed in Paper V by comparing the outcome from the model used with corresponding outcomes from five other empirical models described in that paper.

4 Results

The results presented in Papers I-V are briefly summarised in this chapter. For all results in detail, see the respective paper.

4.1 Impact of parameters and uncertainties in GHG estimates of milk (Paper I)

Paper I assessed and compared the national average GHG estimates for milk (*i.e.* milk CF) for Sweden (SE) and New Zealand (NZ). The milk CF for SE was estimated to be 1.16 kg CO_2e/kg ECM, where the contribution of CH_4, N_2O and CO_2 was 50%, 32% and 18%, respectively. These GHG and their emissions from the various sources are illustrated in *Figure 6*. The milk CF for NZ was estimated to be 1.00 kg CO_2e/kg ECM and the same GHG prediction models and emissions factors (EF) were used for both SE and NZ.

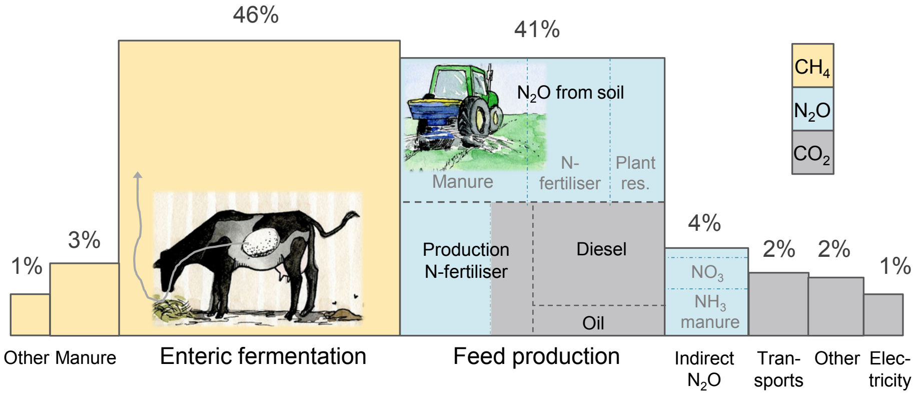

Figure 6. Share of greenhouse gases from different parts of the milk production chain (*i.e.* in a life cycle perspective until milk leaves the farm) for average Swedish milk production in 2005, expressed as carbon dioxide equivalents per unit of milk. Box area represents the share of emissions contributed by that box. (Flysjö *et al.* (2011b); Paper I)

A number of different parameters (*i.e.* constants) and variables (*i.e.* input data characteristic for the studied system) are used to estimate GHG emissions from milk production. Several of these were tested in this study for their influence on estimated milk CF, see *Figure 7*. It was found that the EFs for soil N_2O (due to N-application) and enteric CH_4 as well as the variable 'feed dry matter intake' (DMI) had the largest impact on Swedish milk CF (*Figure 7*).

Large uncertainties are associated with prediction of GHG from biological processes in nature which imply also large uncertainty in the overall milk CF. The impact of uncertainties for the EFs used for soil N_2O and enteric CH_4 were analysed with a Monte Carlo simulation and resulted in an approximately overall uncertainty of ±30% for the milk CF (*Figure 8*). The average CF for Swedish milk had a lower uncertainty range (coefficient of variation (CV) were 16%) compared to the more extensive, low yielding an pasture based dairy system in New Zealand (CV 26%). This concludes that it is inadvisable to compare milk CF without also presenting related uncertainties and without harmonising the calculation methods used.

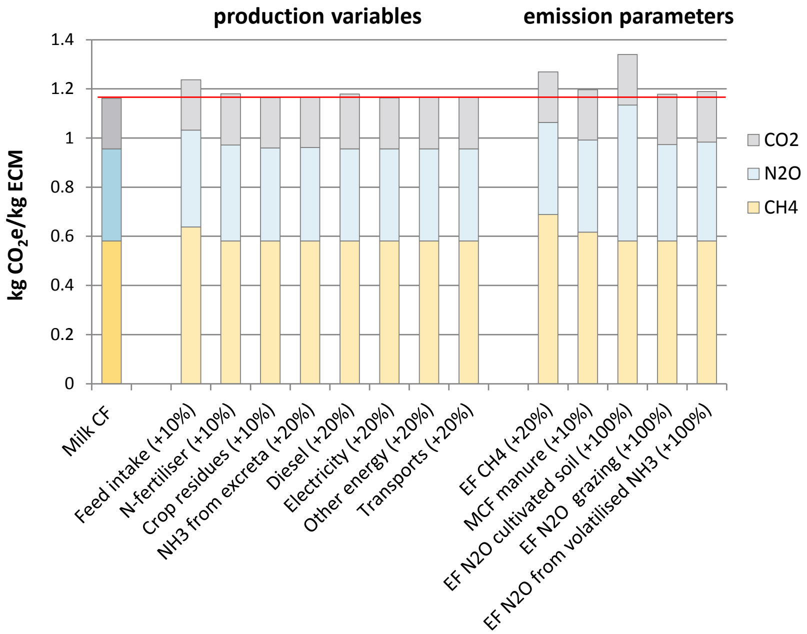

Figure 7. Change in estimated greenhouse gas emissions as CO_2 equivalents (conversion factor 1 for CO_2, 25 for CH_4 and 298 for N_2O) per unit energy corrected milk (ECM), on changing one production variable or emissions factor (EF) and methane conversion factor (MCF) at a time. The first bar and the horizontal line represent the average GHG estimates for Swedish milk in 2005. MCF +10% equals the MCF suggested by IPCC (2006a). (Flysjö *et al.* (2011b); Paper I)

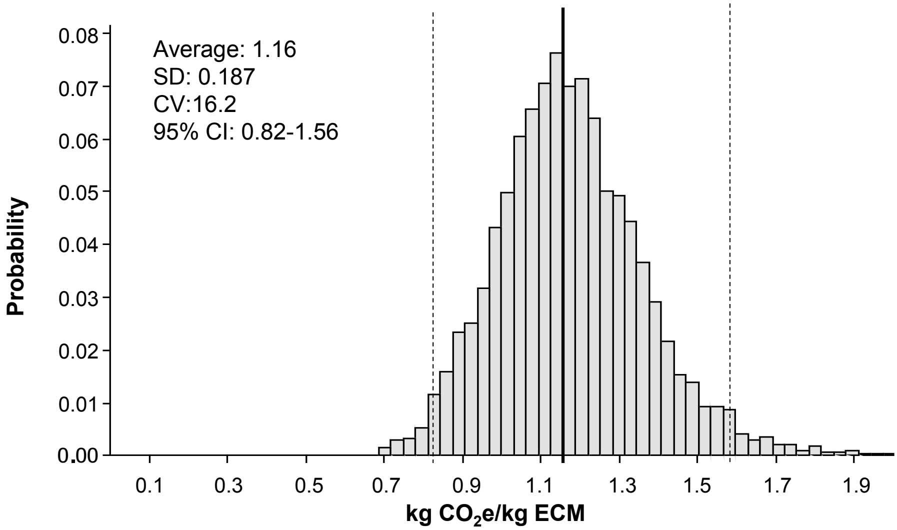

Figure 8. Probability distribution of estimated greenhouse gas emissions per kg energy corrected milk (ECM) for Swedish average milk production in 2005 due to uncertainties in emission factors for enteric CH_4 (Clark, 2001) and N_2O from soil (IPCC, 2006b) and as assessed in a Monte Carlo simulation (Flysjö *et al.* (2011b); Paper I). Vertical dotted lines indicate the predicted 95% confidence interval (from 2.5% to 97.5%).

4.2 Variation in CF of milk due to management differences (Paper II)

Management practices differ between dairy farms and thus a variation in production data (*e.g.* milk yield, feed intake and roughage share in the rations) can be expected between farms. The impact of this on the average Swedish milk CF was analysed in Paper II. The variation found among a large set of dairy farms is presented in *Table 5*. By using the variation for the individual variables ‘milk yield’, ‘feed DM intake’ and ‘EF enteric CH_4’ (all correlated to individual DMI), ‘N content in feed’, ‘N fertiliser rate’ and ‘diesel used on farm’) in a Monte Carlo simulation, we estimated the variation in Swedish average milk CF to be at least ±17% (*Figure 9*). This variation implies that the potential exists to reduce GHG emissions from Swedish milk production. The variation was assessed only for dairy cows, and it is likely that it would have been larger if the total dairy herd had been analysed, *i.e.* if emissions from replacement heifers had also been included. The variation was mostly due to, and equally affected by, CH_4 and N_2O emissions.

Table 5. *Basic statistics on parameters for milk production (n=1051), N-fertiliser rate (n=920) and diesel use (n=46) collected from Swedish dairy farms. Values marked in bold were used in a Monte Carlo analysis (Henriksson et al. (2011); Paper II)*

Parameter	Mean	s.d.	CV[a] (%)	Q_1	Q_2
ECM produced (kg ECM/cow per year)	9 386	983	**10.5**	8 794	10 000
ECM delivered[b] (kg ECM/cow per year)	8 886	980	11.0	8 293	9 505
Delivered share (%)	94.6	2.6	**2.8**	93.5	96.4
Protein in milk (%)	3.35	0.21	6.2	3.30	3.38
Feed DMI (kg DMI/cow per year)	6 534	448	6.9	6 276	6 822
Feed DMI_{ECM} (kg DMI/kg ECM produced)	0.70	0.054	**7.66**	0.67	0.73
Metabolisable energy (10^3 MJ/cow per year)	77.8	6.08	7.8	74.2	81.8
Protein in DMI (% crude protein)	17.2	0.8	4.6	16.8	17.7
N content in DMI (g N/kg DMI)	27.5	12.8	**4.6**	26.9	28.3
Roughage share (%)	52.5	5.5	10.4	49.1	55.0
Enteric CH_4[c] (kg CH_4/cow per year)	125.4	8.1	6.5	120.7	130.8
EF[d] CH_4 (g CH_4/kg DMI)	19.3	1.5	**7.7**	18.4	20.1
FCE (kg ECM/kg DMI)	1.44	0.10	7.0	1.37	1.50
Nitrogen efficiency (kg N_{ECM}/kg N_{DMI})	26.7	1.96	7.3	25.6	27.9
Excreted N[e] (kg N/cow per year)	128.8	13.0	10.1	120.9	136.5
N-fertiliser rate (kg N/ha)	85	33	**38.5**	64	107
Diesel on farm (l/ha)	113	35	**31.2**	88	134

s.d.=standard deviation, Q_1=lower quartile, Q_2=upper quartile, ECM=Energy corrected milk, DMI=dry matter intake, EF=emissions factor, FCE=feed conversion efficiency,

[a]Coefficient of variation, average variance of the mean value

[b]ECM produced excluding fresh milk fed to calves and milk waste due to infections and pharmaceuticals

[c]Calculated with the method of Lindgren (1980)

[d]Calculated from enteric CH_4 and feed DMI

[e]N in DMI minus N in milk produced, calf and gain in weight.

Among the individual production data, the largest variation was found for synthetic N-fertiliser rate (*Table 5*). However, this variation did not correspond to the magnitude of the total milk CF variation, as N from manure had a narrower range of variation and represented a larger proportion of N applied to soil. An interesting aspect of the use of synthetic N-fertiliser and manure was revealed in Paper II. As it is reasonable to expect a correlation between stocking rate (*i.e.* number of livestock units per hectare) and N-fertiliser rate per hectare, this was analysed. However no correlation was found, meaning that despite an increase in stocking rate (*i.e.* larger amounts of manure per hectare), synthetic N-fertiliser dose was not reduced (*Figure 10*). This implies that the potential exists to reduce GHG emissions at farm level by increased utilisation of manure N.

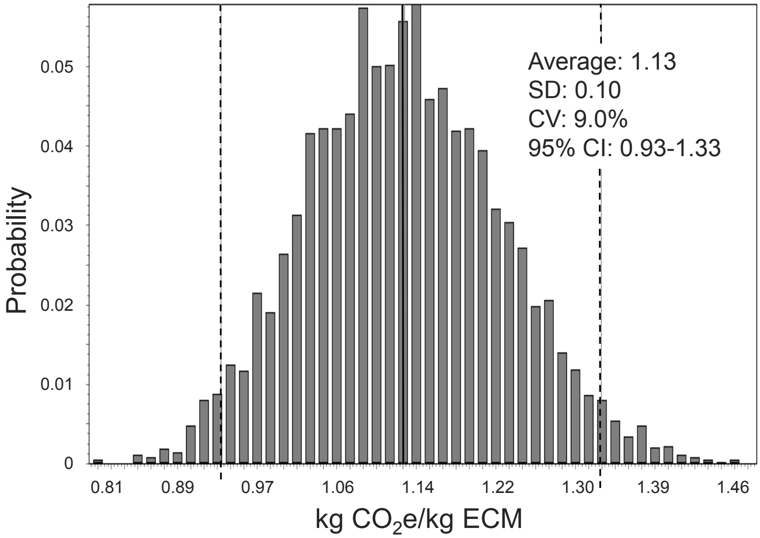

Figure 9. Frequency distribution of greenhouse gas emissions per unit of energy corrected milk (ECM) as a result of variation in input data on farm level, based on a Monte Carlo analysis in Sima Pro (Henriksson *et al.*, 2011; Paper II). Vertical dotted lines indicate the predicted 95% confidence interval (from 2.5% to 97.5%).

As feed production contributes most to milk CF, we calculated the amount of milk produced per unit feed intake, *i.e.* feed conversion efficiency (FCE), for dairy farms in the dataset and found a variation of 1.1-1.7 kg ECM/kg DMI. This implies that the potential exists to reduce GHG emissions at farm level by increased feed utilisation efficiency.

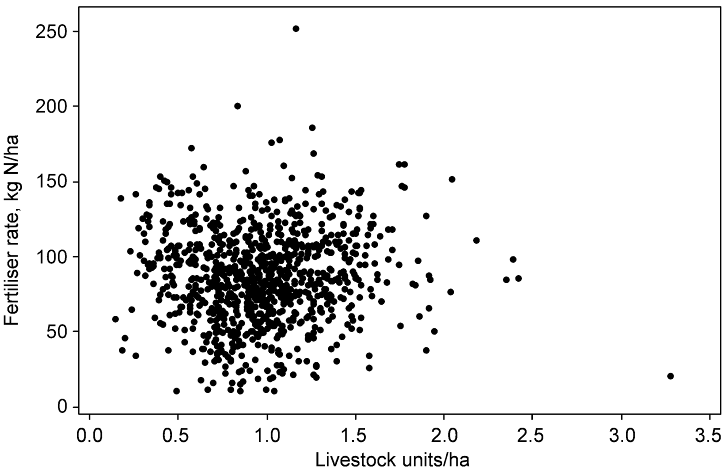

Figure 10. Correlation between synthetic N-fertiliser rates (kg N/ha) and stocking rates (livestock units/ha) on 920 Swedish dairy farms (Henriksson *et al.* (2011); Paper II).

4.3 Impact of feed rations on milk CF (Papers III-V)

Papers III-V studied feed rations from five geographical and climatically different regions for their impact on GHG emissions from feed production, referred to as ration CF or specific feedstuff CF (Papers III and IV), land requirement (Paper IV) and emissions of enteric CH_4 (Paper V). Optimised rations were studied for both multiparous (cows after 2nd calf) and primiparous (cow after 1st calf) cows and replacement heifers, aggregated to a herd ration (*i.e.* feed intake per unit of milk and cow, including replacement heifer), where heifers' share of the DMI constituted 21-23%. Two rations were studied for each region, one with normal quality silage and one with higher quality silage. The characteristics of the rations are shown in *Figure 11* and described in detail in Paper IV together with animal and herd characteristics.

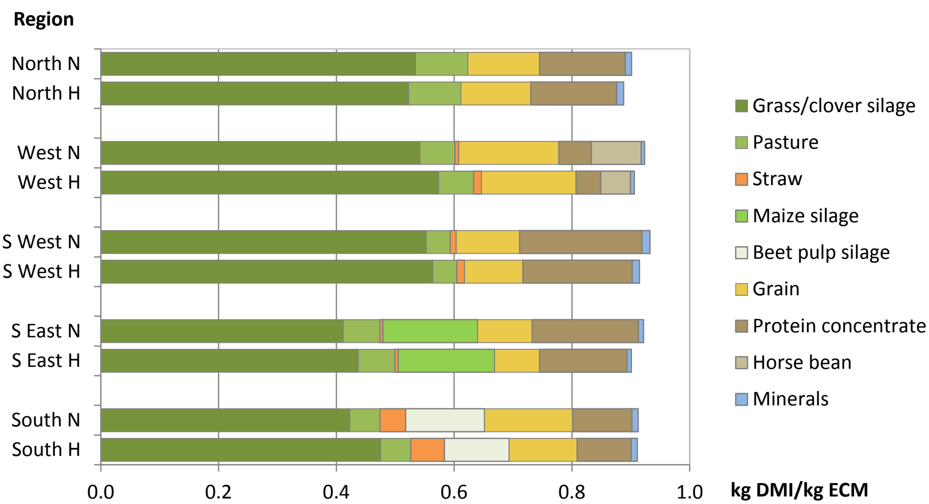

Figure 11. Feed dry matter intake (DMI) of different feedstuffs per kg energy corrected milk (ECM) for five regional feed rations in Sweden with normal (N) and higher (H) nutrient quality grass/clover silage. Herd rations represent the annual milk yield of 9900 kg per cow including heifers (Henriksson *et al.* (2014); Paper IV).

4.3.1 GHG emissions and land requirement for feed production (Papers III & IV)

Regional climate conditions and latitudes affect the production of feedstuffs, especially crop yields, the cultivation conditions required and cultivation practices, which also influence the availability of feedstuffs in the region. As a consequence of this, GHG emissions from feed production and the arable land requirement varied between the rations studied, see *Figure 12* and *Figure 13*, respectively. The ration with the highest estimated GHG emissions (S West) generated 30% more emissions than the ration with the lowest emissions (South).

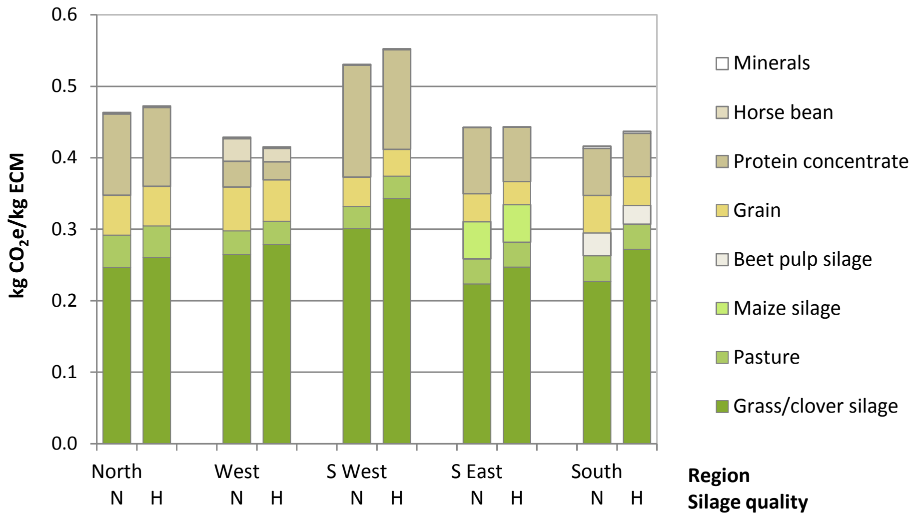

Figure 12. Greenhouse gas emissions from the life cycle of regional feed rations per unit energy corrected milk (ECM) at an annual milk yield of 9900 kg, including heifers and feed losses. Rations include silage with normal (N) or higher (H) nutrient quality. GHG emissions are expressed as CO_2 equivalents using the conversion factor 1 for CO_2, 25 for CH_4 and 298 for N_2O (IPCC, 2007b). Beet pulp silage is from the sugar industry (Henriksson *et al.* (2014); Paper IV).

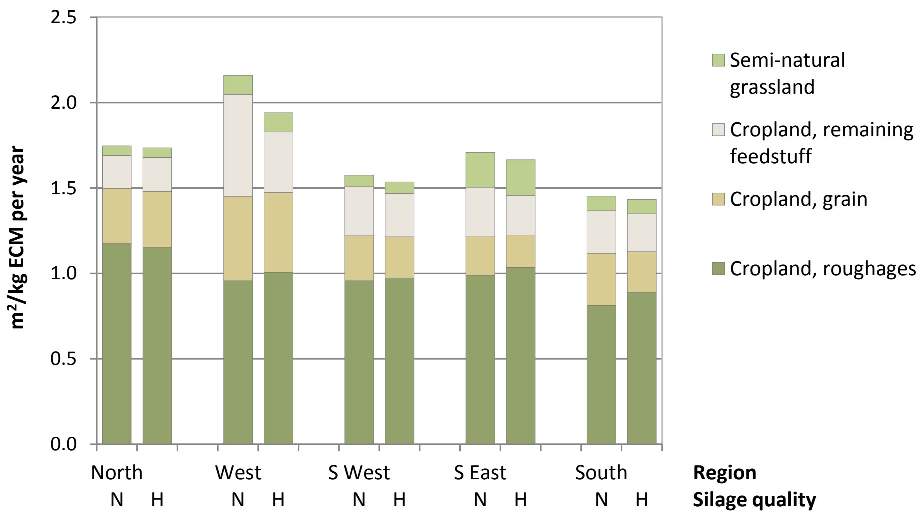

Figure 13. Annual land requirement for regional feed rations per unit energy corrected milk (ECM) at an annual milk yield of 9900 kg, including heifers and feed losses. Rations include silage with normal (N) or higher (H) nutrient quality (Henriksson *et al.* (2014); Paper IV).

Since agricultural land is a limited resource (and may be associated with GHG emissions from LUC), the land requirement was also assessed for the rations. Cultivated land area did not follow the levels of GHG emissions, in fact the largest requirement of land was found for the ration with the lowest GHG emissions (West ration) due to the inclusion of relatively low yielding horse bean. The ration emitting most GHG (S West ration) required significantly less land than the West ration due to higher crop yields (*Figure 13*). Heifers were responsible for about 20% of total emissions for the ration and 25% of the land requirement.

Grass/clover silage was the dominant feed component in the animal rations and contributed more than 50% of the GHG emissions from the rations. In Paper III and IV, production of grass/clover silage was generally estimated to cost more GHG emissions per kg DM than grain, on average 0.54 kg CO_2e/kg DM silage compared with 0.40 CO_2e/kg DM grain. Emissions per unit DM silage varied between regions as a result of yield levels and N application rates (*Figure 14*). When grass silage CF for the different regions was compared, the grass silage with the highest CF (S West) emitted 17% more GHG per kg DMI than the silage with the lowest CF (North) (Paper III). Silage with low emissions had a positive influence on the total ration-based emissions of GHG (*e.g.* West ration) compared with silage with high emissions (S West) (*Figure 12* and *Figure 14*). Losses of silage DM in storage and during feeding activities

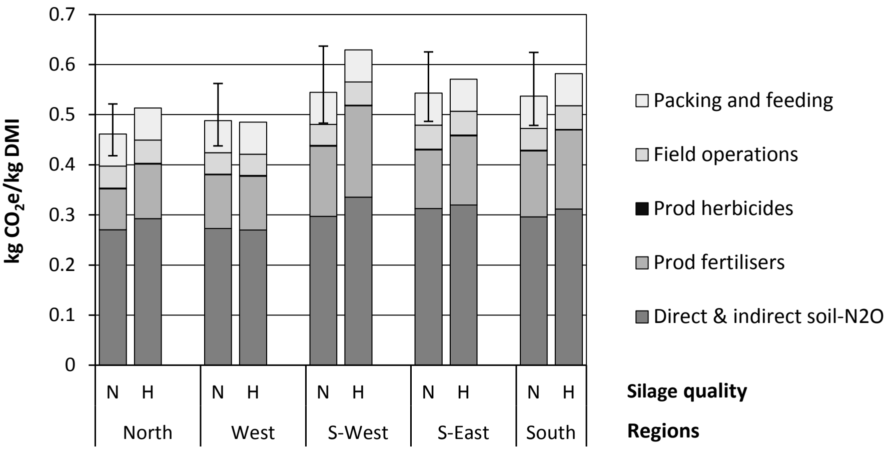

Figure 14. Greenhouse gas emissions (GHG) per unit feed dry matter intake (DMI) from production (Prod) of grass/clover silage with normal (N) and higher (H) nutrient quality for different regions. Error bars show the effect from varying yield level by ±20. GHG emissions are expressed as CO_2 equivalents using the conversion factor 1 for CO_2, 25 for CH_4 and 298 for N_2O (IPCC, 2007b) (Henriksson *et al.* (2013a); Paper III).

were included in estimated silage CF and it was concluded that these losses significantly affected GHG emissions per unit silage DMI (Paper III).

When GHG emissions from production of normal quality silage were compared with those from production of a higher nutrient quality silage, the latter showed general higher GHG emissions per kg DM (average 8%) as a result of increased N-fertiliser rates and additional grass cuts to achieve the higher quality (Paper IV). This effect was also reflected in the total emissions for the feed rations (*Figure 12*).

The CF of other feedstuffs was also shown to influence emissions and the land requirement estimated for the overall rations (*Figure 12* and *Figure 13*) (Paper IV). However, the overall conclusion in Paper IV was that it is the overall composition of the ration that determines the total GHG emissions, rather than GHG emissions per unit DM for different feedstuffs included in the ration.

Maize silage had a positive effect on the CF of the S East ration due to high yields, resulting in 40% lower GHG emissions per kg DM and half the land requirement compared with the grass/clover silage it replaced.

The domestically grown horse bean used in the West ration to replace some of the protein in commercial concentrate products (*e.g.* imported soy meal) had a reducing effect on the CF, but simultaneously increased the land requirement.

Pressed sugar beet pulp, a by-product from the sugar industry, had a positive reducing effect on the CF of the South ration due to its very low CF. By-products from the food industry (another example is dried distiller's grain) generally have a low CF compared with other feed crops, as most of the emissions are allocated to the main product (*e.g.* sugar or ethanol). The same applies for the land requirement.

Soy meal can have a crucial effect on ration CF if CO_2 emissions from LUC are included, but the magnitude of these emissions is highly dependent on methodology and LUC factors used (Paper IV).

4.3.2 Methane emissions from enteric fermentation (Paper V)

Enteric CH_4 production per unit of milk from cows and replacement heifers (38% replacement rate) was predicted for the regional feed rations and for three different milk yields (8900, 9900 and 10900 kg ECM/cow and year). An extra feed ration with high fat (HF) content was added (South HF) to the other rations to compare the effect of increased fatty acids (FA) content on estimated enteric CH_4 production. Estimated enteric CH_4 varied between the rations by on average 5% (*i.e.* the largest difference between the rations as a percentage of the lowest) for each of the milk yields (*Figure 15*). The variation was highly correlated to the amount of DMI for each ration, while content of FA contributed a smaller part of the variation. Thus low DMI and high proportion of FA resulted in low estimates of enteric CH_4 production, *e.g.* for the South HF ration. Increasing the nutrient quality in the grass/clover silage in the dairy cow ration from normal to higher, decreased enteric CH_4 per kg ECM by 2%, mainly because the higher quality silage reduced total DMI.

Heifers contributed around 20% of the CH_4 emissions. When the replacement rate was reduced from 38% to 25%, estimated CH_4 emissions on herd level were lowered by 6%. With increased milk yield, CH_4 emissions per unit of milk were reduced by 1-2%-units, but per cow and year the emissions were increased by approximately 4% for each 1000 kg ECM increase in yield.

Due to the small differences found in enteric CH_4 production between feed rations and silage qualities related to uncertainties in the prediction model, reliable conclusions could not be drawn about the composition of the separate feed rations. In addition, the differences between the rations were not the same for the three milk yields tested.

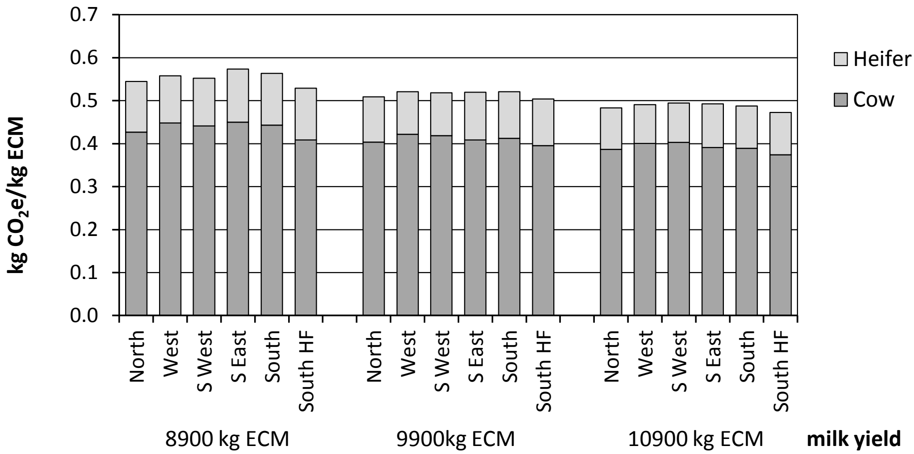

Figure 15. Enteric methane (CH_4) emissions from cows and replacement heifers at 38% replacement rate (*i.e.* 0.89 heifers/cow) for six different feed rations with normal quality silage and for three annual milk yields. The South rations represent two different fat contents, with a 50% higher proportion of fatty acids in the South HF (high fat) ration. Enteric CH_4 is expressed as carbon dioxide equivalents (CO_2e) with the conversion factor 25 (IPCC, 2007b). (Paper V)

4.3.3 Combined impact from feed ration CF and enteric methane emissions (Papers IV and V)

From the combined results from Papers IV and V (*i.e.* around 85% of the total milk CF according to Paper I, see *Figure 6*) it can be concluded that they approximately constitute equal parts, with slightly more for the enteric CH_4 (*Figure 16*). The variation between rations for the combined emissions result followed the same pattern as for emissions from feed production and the magnitude of the difference between highest and lowest emissions was also almost the same (*Figure 16* compared with *Figure 12*). The small reduction in enteric CH_4 production for rations with the higher nutrient quality silage could not compensate for the increased emissions arising when the better silage was produced, *i.e.* emissions caused by increased N-fertiliser rate and an extra cut. Heifers contributed around 20% of the combined emissions.

There was a significant difference in variation between GHG emissions from enteric CH_4 production and from feed production, with emissions from feed production varying on average five-fold more than emissions from enteric CH_4. This finding is important as it highlights the potential role of feed production in future mitigation measures at farm level.

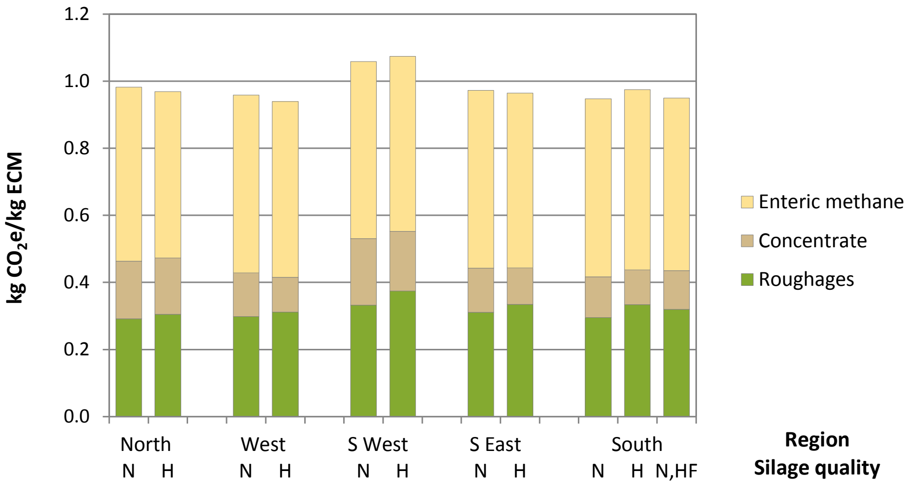

Figure 16. Greenhouse gas emissions (GHG) from feed production and enteric fermentation per kg energy corrected milk (ECM) for different regional feed rations with normal (N) and higher (H) nutrient quality silage for the annual milk yield of 9900 kg per cow including heifers and feed losses. South region also include a ration with higher fat content (HF) and normal quality silage. GHG emissions are expressed as CO_2 equivalents using the conversion factor 1 for CO_2, 25 for CH_4 and 298 for N_2O (IPCC, 2007b). (Henriksson *et al.*, 2014; Papers IV and V).

5 Discussion

The overall aim of this thesis was to contribute new information that could lead to more climate-smart milk production in intensive dairy production systems (especially in Sweden). When doing this in a systems perspective using LCA as a method, it is crucial to be aware of the reliability of the calculated results before these are used to define mitigation measures. The overall GHG estimates for agricultural production depend on methodological choices made in the performance of the LCA in terms of *e.g.* system boundaries, input data and choice of prediction models for GHG emissions. Especially important are models and parameters used for quantification of biogenic GHG emissions and the quality of used input data (Papers I, II and VV).

Feed plays a central role for the magnitude of GHG emissions from milk production, as it is the driving force for the two major GHG sources, contributing around 85-90% of the total emissions, *i.e.* feed digestion (enteric CH_4) and feed production (N_2O and CO_2) (Paper I). Feed DMI is estimated to explain 85% of the enteric CH_4 produced (Ramin & Huhtanen, 2013). It also affects milk yield, which is the other critical factor for milk CF value. Milk produced per kg DMI expresses the feed efficiency of the cows or the herd, which together with feed cultivation practices and feeding strategies are highly important elements affecting the final milk CF. Consequently, they are also important in terms of mitigation measures (Papers III and IV). Furthermore, the nutritional composition of feedstuffs and feed rations affects enteric CH_4 production (Paper V).

5.1 Reliability of predicted GHG emissions

Since the aggregated GHG emissions from the whole milk production chain cannot be measured, researchers depend on models to estimate these emissions and the calculated values include various levels of uncertainty (Zehetmeier *et al.*, 2013; Basset-Mens *et al.*, 2009a; Paper I). Some important aspects of the uncertainty found in GHG estimates of milk are discussed below, structured in a three-dimensional concept: *Location*, *i.e.* where the uncertainties are found; *nature*, *i.e.* what is causing the uncertainty; and *level*, *i.e.* the magnitude of uncertainty. This structure follows definitions suggested by Walker *et al.* (2003) (*Figure 17*). Structuring and classifying uncertainties in this way can help in understanding their different properties, in order to find possible ways to reduce their magnitude and to perform as accurate a CF analysis as possible (Rypdal & Winiwarter, 2001). Defining the nature of the uncertainty is important as it affects the level to which the uncertainty can be reduced.

The uncertainty of the variable grass yield can be used to explain figure 17. The *location* for this uncertainty is mainly found in the input data. Its *nature* is epistemic, i.e. the uncertainty is caused by poor measurement and statistics, as well as there is a natural variability of yields due to *e.g.* annual weather conditions. The *level* of the uncertainty can be assumed to be high as grass yield is seldom weighed.

Uncertainties related to the overall issue of anthropogenic GHG emissions and the magnitudes of their effect on global warming (*i.e.* their GWP) are omitted from this discussion.

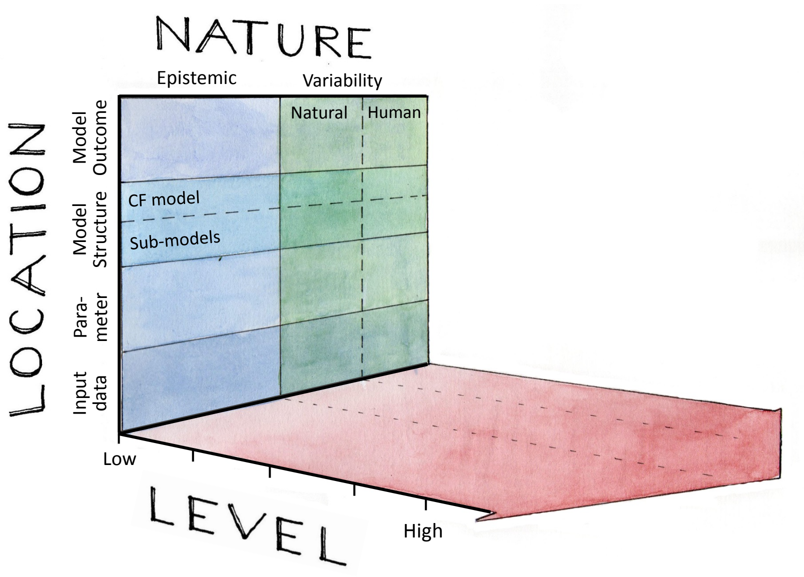

Figure 17. The three dimensions of uncertainty: *location* (uncertainties in input data, parameters, model structure and model outcome), *nature* (uncertainty due to imperfection of knowledge (epistemic) or inherent variability) and *level* (gradient of the magnitude of uncertainty) after a concept suggested by Walker *et al.* (2003).

5.1.1 Level and nature of uncertainty

Different levels of uncertainty in milk CF

The level of uncertainty can be placed on a scale from exact knowledge (*i.e.* lack of uncertainty) to total ignorance (*i.e.* we do not know what we do not know) (Walker *et al.*, 2003). In estimates of milk CF different levels of uncertainty will be incorporated and these will vary widely between models, parameters and input data, see *Table 6* and *7*. The uncertainty levels in these tables are arranged on a relative scale and are based on knowledge and experience from Papers I-V. However, it is likely that uncertainty levels differ between nations and production systems due to the models and parameters used and the availability of input data.

There is a clear distinction in level of uncertainty between GHG emissions from technological processes (*e.g.* from combustion of fossil fuel and synthetic N-fertiliser) and from biological processes that occur in nature (*i.e.* from animals, soil and manure) (*Table 6*). Emissions from technological processes can be estimated with much larger certainty, as they are known in detail and can be measured in controlled environments. For biological processes the opposite applies, as they are governed by numerous factors that are beyond human control and thus measured in an uncontrolled environment.

Nature of uncertainty in milk CF

The uncertainty in milk CF is by nature a mixture of epistemic uncertainty, *i.e.* related to our understanding of the system, and variability uncertainty (*Figure 17*). The latter relates to the unpredictability of natural processes in nature. The reason for distinguishing between these two is in order to determine how to address and reduce them. Epistemic uncertainty can be reduced with increased knowledge, *e.g.* research and measurements, while the inherent variability will remain. However, with better ways to capture and include it in GHG estimates, it could improve milk CF reliability.

Epistemic uncertainty is found *e.g.* in the structure of the models used to calculate GHG emissions from various sources, as exemplified by the large uncertainty range for milk CF (around ±30%) modelled in Paper I. Inherent variability is found in all biological processes such as N_2O or CO_2 production in soil and CH_4 production in the animal rumen, but it is also found in human behaviour, *e.g.* farm management practices or methodological choices in LCA. The variation due to management practice can be fairly large, ±17% according to Paper II. Although knowledge of the complex biological processes is constantly increasing, the inherent variability of these processes involves large complexity when modelling them and thus makes the development of good prediction models difficult. Causes of uncertainty are further described in section 5.1.2 for the different locations of uncertainties.

5.1.2 Location of uncertainties

In GHG estimates of milk, uncertainties are found in the structure of the model, in model parameters (*i.e.* the constants in the model), in model input data (variables) and in the outcome of the model (*Figure 17*).

Uncertainty in model structure

Firstly, a distinction can be made between the overall CF model that estimates the total GHG emissions from milk production and the constituent sub-models that estimate the individual GHG emissions or input data (*e.g.* feed intake or N in manure).

The overall CF model will include epistemic uncertainty depending on how well the system analyst knows the system under study and its sub-processes, but also a type of variability due to human behaviour. There will be differences in how single CF for milk is assessed even if the well-established and ISO standardised method of LCA and special guidelines, such as IDF (2010), for milk CF estimates are used (Crosson *et al.*, 2011; de Vries & de Boer, 2010; Gerber *et al.*, 2010; Thomassen *et al.*, 2008). This is due to the individual methodological choices that have to be made in different studies, which will affect the outcome of the assessment. Methodological choices include how functional units are defined, where the system boundaries are drawn and what sub-models that are chosen when estimating the CF. Another methodological choice that can affect milk CF dramatically is how the emissions are allocated between milk and other co-products from the system, as clearly illustrated by Flysjö *et al.* (2011a) and Zehetmeier *et al.* (2013). The large impact that methodological choices can have on the outcome of CF calculations clearly suggests that milk CF values should not be compared unless estimated uniformly (Paper I). For the same reason, it is also important to have high transparency in CF estimates.

Uncertainties in the structure of the sub-models used are of both an epistemic and variability nature. They are epistemic as they are very dependent on current knowledge of the actual process and accuracy in data forming the knowledge, which can be affected by *e.g.* measurement techniques. They include variability uncertainty due to the inherent randomness of biological processes. This variability is the major reason why it is difficult to develop detailed prediction models with low prediction error for biogenic GHG emissions. Good prediction models are however needed to reduce the uncertainty levels of these emissions. Detailed models are generally presumed to make better predictions (Alemu *et al.*, 2011) however they are simultaneously likely to be more sensitive for errors in variables and parameters which can increase uncertainty (Snowling & Kramer, 2001). If a model is very complex it can also be difficult to run if it requires input data that are difficult to obtain.

The most important methodological choices regarding uncertainty in the present thesis involved the choice of sub-models for soil N_2O and enteric CH_4, the exclusion of CO_2 from LUC and the methodology to estimate feed rations.

The simple and undifferentiated model used to calculate soil N_2O was chosen as it is commonly used in LCA, despite its large uncertainty range, and it was presumably the sub-model that caused the largest uncertainty in CF estimates presented in this thesis. In contrast to this highly simplified and general model, nationally adapted and more detailed models for NH_3 emissions from manure and leached soil NO_3^- were used. However, the impact on milk CF from these emissions are significantly smaller than direct soil N_2O emissions (*Figure 6* and *Table 6*). Different prediction models for enteric CH_4 were compared in Paper V, which indicated that choice of enteric CH_4 model affects the results, but the uncertainty level in enteric CH_4 predictions was significantly lower than that for soil N_2O according to Paper I and Zehetmeier *et al.* (2013).

The exclusion of CO_2 from LU and LUC can have a significant impact on milk CF and are further discussed in the sub-sections '*Uncertainty in model outcome*' and '*A crucial methodological choice of system boundary in milk CF*'.

The method used to obtain the regional and comparable feed rations assessed in Papers IV-V involved some degree of subjectivity, as they were made by five regional feed advisors (*i.e.* inherent variability due to human behaviour). However, the method was chosen as we wanted to analyse realistic rations that we assumed would be best provided by feed advisors with long-lasting experience and knowledge of feed conditions in their respective region. The rations might have been more comparable if the same person had formulated all of them, but this might have lowered the regional differences we wanted to capture. The same feed evaluation system with predefined settings of lactation curves, herd performance *etc.* was used, ensuring comparability of the rations.

Uncertainty in model parameters

The uncertainty in model parameters and EF is of differing levels and nature. Empirical uncertainty derives *e.g.* from different measurement techniques and how the trial set-ups represent the systems or processes studied. Variability uncertainty is incorporated in empirical data on which parameters and EF are based. For example, soil N_2O emissions are extremely variable over space and time due to soil properties, climate conditions, microbial communities and soil management (Hénault *et al.*, 2012), which creates large uncertainty levels in model parameters used in prediction models for biogenic GHG (*Table 6*). N_2O from soil is one of the most influencing parts to the overall uncertainty in milk CF (*Figure 7*) especially if the IPCC's EF for soil N_2O is used (Paper I; see also Zehetmeier *et al.* (2013)). This EF has an uncertainty range of 0.003-0.03 kg N_2O-N/kg N applied (IPCC, 2006b). The other main GHG in milk CF estimates, enteric CH_4, also varies due to *e.g.* feed intake, properties of feedstuffs, the rumen microbial flora and differences in animal genetics, which indicate the use of detailed prediction models for enteric CH_4, especially when different feeding strategies are compared as in Paper V. Production of enteric CH_4 is possible to study in a somewhat more controlled environment than emissions from soil, which results in lower uncertainty level for parameters in enteric CH_4 prediction models than in models predicting soil N_2O emissions (*Table 6*).

Parameters and their level of uncertainty influence milk CF estimates differently depending on the features of the system under study. For example, the EF for soil N_2O emissions caused by excreta dropped on grazing had a larger influence in the pasture-based milk production systems in New Zealand than in a milk production system where grass from grazing was a minor part of animal feed intake such as the Swedish production systems (Paper I).

It is reasonable to assume that model parameters predict best if they represent conditions similar to those studied, especially for emissions that are influenced by regional climate conditions, such as biogenic CO_2 from soil or CH_4 emissions from stored manure. For the latter, we used a methane conversion factor derived from a Swedish study, which was only half the value proposed by IPCC guidelines and thus had a significant impact on manure CH_4 emissions. Another example is the EF for enteric CH_4 used in Paper I, i.e. an EF developed for NZ conditions and used in the NZ inventory report, which might gave better predictions for the New Zealand milk production system than for the Swedish. However, when compared with the Swedish prediction model used in Paper II, the total annual CH_4 emissions per cow did not differ greatly between the models and thus had a minor effect on the average milk CF.

Table 6. *Estimated relative level of uncertainty for sub-model structures and parameters (constants) used for calculating greenhouse gas emissions (GHG) or input variables (Input) in milk carbon footprint (CF) estimates and their relative significance for milk CF estimates in this thesis.*

Level	Model and parameter	Calculating	Significance for milk CF		
			Large	Medium	Small
Low uncertainty	Fossil CO_2 – diesel	GHG		x	
	N_2O fertiliser production	GHG		x[a]	x[a]
	CO_2 fertiliser production	GHG			x
	Fossil CO_2 – other energy	GHG			x
Quite low uncertainty	Feed evaluation model[b]	Input		x	
	N in excreta	Input		x	
Moderate uncertainty	CH_4 from enteric fermentation[c]	GHG	x		
	CH_4 from manure	GHG			x
	N in spread manure	Input	x		
	NO_3^- leaching from soil	Input			x
	NH_3 from manure	Input			x
Quite high uncertainty	Plant available N from manure	Input		x	
	N in plant residues	Input			x
High uncertainty	N_2O from soil	GHG	x		
	N_2O indirect[d]	GHG			x
	Biogen CO_2 from cultivated soil	GHG	x		
	Biogen CO_2 from land use change	GHG	x		

[a]Refers to production of ammonium nitrate and the significance for milk CF depending on N_2O refinement level in fertiliser plants (the better the refinement the smaller the impact). Medium impact refers to results in Flysjö *et al.* (2011b).

[b]NorFor (Volden, 2011)

[c]Uncertainty level depending on the model used

[d]N_2O released due to volatilisation of NH_3 and leakage of NO_3^-

A crucial parameter for the outcome of the final GHG estimate, although not assessed in the present thesis, is the GWP of CO_2, CH_4 and N_2O used to convert them to CO_2-equivalents. This parameter highly influences the contribution of each GHG to the total CF. The GWP are estimated for a certain time perspective, *i.e.* in a 20, 100 or 500 year perspective, where the 100 year perspective (GWP_{100}) is commonly used in LCA. Uncertainties in the present GWP_{100} defined by IPCC are large, ±35% (IPCC, 2007b). One reason why uncertainties in N_2O estimates have a large impact on milk CF (Paper I) is the high GWP_{100} for N_2O. The GWP_{100} for CH_4 and N_2O have also been changed over time relative to CO_2, from 21- to 23- to 25-fold for CH_4 and from 310- to 296- to 298-fold for N2O in the 2nd, 3rd and 4th IPCC assessment report, respectively (IPCC, 2007b; IPCC, 2001). In the 5th assessment report just recently published, further changes in GWP_{100} for these gases are proposed (Myhre *et al.*, 2013). Now two different GWP_{100} values are estimated for each GHG depending on whether 'climate-carbon feedbacks (ccf)' are included or not. These are 28 and $34_{(ccf)}$ for CH_4 and 265 and $298_{(ccf)}$ for N_2O. Changes in the GWP parameter not only change the outcome of milk CF, but also our interpretation of how various activities or parts of milk production contribute to climate change. For example, an increase in the GWP for CH_4 would further increase the dominance of enteric CH_4 in milk CF and would thus affect the results in this thesis and their interpretation as regards what mitigation measures to prioritise.

Uncertainties in model input data

Uncertainty levels found in model input data (*i.e.* the data that characterise the milk production system) vary widely, from *e.g.* a very high certainty in milk yield data to the highly uncertain data on grass yields and feed losses (*Table 7*). The nature of uncertainty is related to inherent variability and to how well data are measured and recorded (epistemic uncertainty). The former is reflected in nature by *e.g.* crop yields varying with seasonal weather conditions and in human behaviour by variations in management practices between and within farms (*e.g.* feeding and fertiliser application). The level of uncertainty in input data is not constant. As an example, data on crop yields from national statistics used in a national milk CF estimate can have larger uncertainty than corresponding data obtained at farm level if crop yields have been thoroughly and annually measured, or *vice versa* if crop yields are not measured.

The uncertainty level of the input data that constitute the functional unit (FU) in a CF estimate is important for the CF reliability. Fortunately, the FU used in estimated milk CF in present thesis, *i.e.* "delivered amount of energy corrected milk" (Papers I and II) can be regarded as the most certain value in these calculations since it is recorded by the dairy and can be obtained both at farm level or from national official statistics. The milk yield data produced also have a high certainty due to the national official milk recording scheme, which has a participation rate of 85% of Swedish dairy cows (Swedish Dairy Association, 2011).

The uncertainty levels for "feed DM consumed for a specified milk yield", which is the FU used in ration CF estimates in Paper IV, can be presumed to be fairly certain due to the detailed feed evaluation model NorFor, which was used to ensure that the relationship between feed intake and milk yield was realistic.The FU "silage DMI" used for the grass silage CF estimates is much more uncertain, mainly due to the highly uncertain correlation between crop yield and N-fertiliser rate, as also concluded in Paper III. Thus, it will influence the reliability of ration CF estimates.

When seeking to improve reliability in milk CF estimates by reducing the uncertainty in the input data, high priority should be given to input data with large significance for milk CF. In addition to milk yield, these input data are feed DMI, N-application rate to soil, dairy cow replacement rate and crop yields, whereas input data on *e.g.* transport and electricity use are of small significance for GHG estimates of Swedish milk (*Table 7*).

Feed DMI has major significance for milk CF (*Figure 7*), as feed production constitutes a major part of estimated GHG emissions. The DMI of roughage is likely to include the largest level of uncertainty, especially if fed *ad libitum* or grazed, whereas concentrate rations are likely to be fed and recorded with higher precision, *e.g.* with the use of transponder system. Purchased concentrate is also recorded in the farm accounts, whereas grain cultivated and stored on the farm is not. An important aspect for feed DMI is its correlation to milk yield. However, this correlation is affected by management practices and, due to variability in *e.g.* feed nutrient content, over-feeding and feed losses, it is expected to vary between farms, as shown in Paper II (*Table 5*).

N-fertiliser application rate influences milk CF, as it is strongly correlated to soil N_2O emissions, *e.g.* in Paper I a small increase (around 6 kg/ha) in average synthetic N-fertiliser rate increased milk CF by almost 2% (*Figure 7*). Furthermore, synthetic N-fertiliser contributes additional GHG emissions from its production. The uncertainty level for these input data is low due to the known and stable N content in N-fertilisers and as accurate data are easily obtainable at farm level, *e.g.* from farm accounts. N-fertiliser rates can be expected to vary widely due to *e.g.* crop cultivation conditions and how individual farmers estimate the amount of N required by the crop (*Table 5*). However, N-fertiliser rates used on farms are also related to manure application rates and vary depending on how individual farmers choose to manage, analyse and evaluate the nutritional effect of available manure. Although manure is an important nutrient resource, it is utilised very differently on different farms, as was observed in Paper II (*Figure 10*). The N content in the manure produced can be calculated in CF estimates as the N balance for the animal. By further estimating NH_3 emissions from housing to manure spreading, the overall amount of N applied as manure can be estimated (Papers I and II). However, there is a risk of calculated values underestimating total N-fertiliser rates unless differences in how farmers account for the plant-available N in applied manure are considered.

Replacement rate has major significance for milk CF, as the number of replacement heifers constitutes a significant part of estimated GHG emissions, *e.g.* 20% of the GHG from feed production and enteric CH_4 in Papers IV and V) (*Table 7*). Zehetmeier *et al.* (2013) found that uncertainty regarding replacement rate affected the overall uncertainty level of calculated milk CF more than uncertainty in estimated enteric CH_4. Data on replacement rate in Sweden can be considered to have a low uncertainty level, as can other herd performance data (*e.g.* fertility, age distribution, reproduction and animal health) as these are recorded in the Swedish official milk recording scheme.

Crop yield data are important for milk CF estimates, especially for grass/clover and forage maize since they constitute the largest part of the herd's feed intake. The level of uncertainty on crop yields is also important, as it determines the use of cultivated land, which can affect soil N_2O emissions and CO_2 from LU and LUC (*i.e.* the lower the yield, the more land required) (Paper IV). The largest uncertainty level was found for roughage yields, as these are rarely measured at farm level and the available national statistics are thus based on farmers' estimates (*Table 7*).

Data on diesel and electricity use on the farm are fairly certain, as accurate data can be obtained from farm accounts. However if farmers use contractors for field operations, accurate data could be more difficult to obtain. Data specified for various field operations or processes are likely to be more uncertain as they are rarely measured at farm level and not officially recorded.

Data on feed DM losses can have a significant impact in CF estimates for feed rations or single feedstuffs, especially roughage (Paper III). The uncertainty level for data on feed losses in this thesis can be assumed to be large due to the comparatively few studies performed (new national studies has however been initiated; http://www.lantbruksforskning.se). DM losses from storage of ensiled roughage can be expected to vary widely due to current circumstances and the default value used in Papers III and IV (13%) is reasonable as an average, but probably has a larger variation than analysed in Paper III (Spörndly, 2014).

Feed nutrient data are also important for feed ration CF, as they affect the ration composition. This applies especially for roughage feed, where the nutrient quality of the feed in a feed evaluation model needs to correspond to the input data used to produce the same feed (*e.g.* exemplified in Papers III and IV). The uncertainty level for this relationship is presumably high, as it involves both natural inherent variability and variability in cultivation practices.

The significance of various input data for estimated milk CF can however be expected to vary between milk production systems. In the Swedish system, data on grass yields for silage showed larger significance than grazed grass yields, as grazing constitutes a minor part of feed DMI in Sweden (Papers I, III and IV). The opposite was found for the grazing-based systems in New Zealand (Paper I).

Table 7. *Estimated relative level of uncertainty in input data (variables) that characterise Swedish milk production and used in milk carbon footprint (CF) estimates, as well as their relative significance for milk CF estimates in this thesis*

	Input data	Significance for milk CF		
		Large	Medium	Small
Low uncertainty	Milk yield	x		
	Replacement rate	x		
	Other herd performance data[a]		x	
	Electricity use			x
Quite low uncertainty	Synthetic N-fertiliser application rates	x		
	Total diesel use at farm[b]		x	
	Nutrient in concentrate			x
Moderate uncertainty	Feed intake - concentrate	x		
	Crop yields[c]		x	
	Diesel use for specified field operations[d]		x	
	Transport pre-farm			x
Quite high uncertainty	Feed intake – roughage	x		
	Feed nutrient data – roughage		x	
	Manure N application rates		x	
High uncertainty	Grass yields[e] – silage	x		
	Feed losses		x	
	Grass yields - grazing			x[f]
	Feed intake - grazing			x[f]

[a]Ratio of cows after first calving and older cows, age at first calving
[b]When obtained directly from farm
[c]Excluding roughage and grazing
[d]With total diesel use aggregated from the use of individual field operations
[e]Including forage maize
[f]The small significance relates to a marginal dry matter intake from grazing in the cows' annual feed ration

Uncertainty in model outcome

Levels of uncertainties in input data and parameters will be accumulated in the outcome of each sub-model, as well as in the overall milk CF model (*Figure 18*). This was illustrated as separated results in Papers I and II (*Figure 8* and *9*). The great level of complexity in the biological processes emitting GHG induces a high sensitivity for input data and parameters in the sub-models predicting these GHG. High sensitivity combined with large uncertainty levels will increase the uncertainty in the model outcome (Snowling & Kramer, 2001). To improve the outcome from the overall CF model, it is thus crucial to reduce uncertainties in the sub-model structures, parameters and input variables to which the CF model is most sensitive. In the present thesis this was primarily the model structure and parameters for prediction of soil N_2O emissions and enteric CH_4 production and the input variables for milk yield, feed intake and N applied to soil (*Table 6* and *7*). Data associated with roughage feed were also important in this regard. Priority in reducing uncertainty levels should also be given to those parts of the milk production chain that contribute most emissions to milk CF, as this would affect the overall reliability of milk CF the most (Paper I).

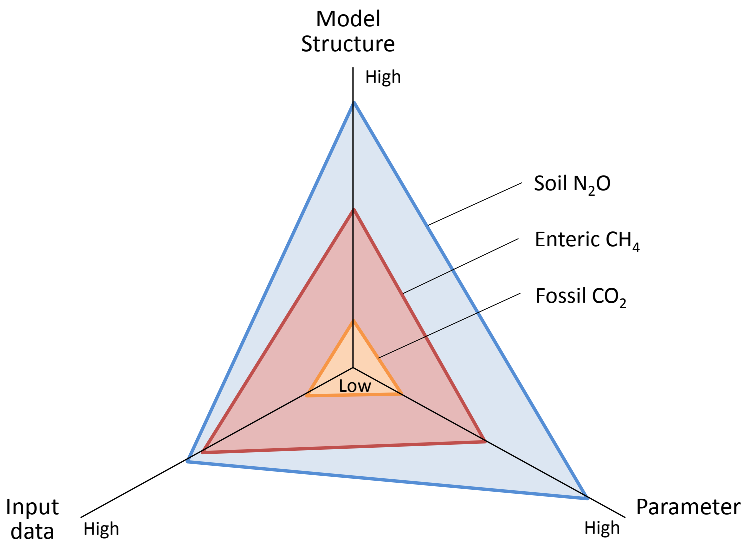

Figure 18. Conceptual illustration of combined uncertainty from uncertainties in model structure, model parameters and input data for prediction of greenhouse gases (GHG) from three different processes (i.e. soil N_2O, enteric CH_4 and fossil CO_2) included in total GHG estimates of milk production. Uncertainty levels on axis ranges from low in centre to high.

The level of expertise of the analyst regarding the system under study is likely to influence the uncertainty in the outcome of estimated milk CF. A high level of expertise about the agricultural activities included in on-farm milk production will increase the analyst's ability to evaluate the accuracy in input data characterising the milk production system (*e.g.* feed intake relative to milk yield, fertiliser and manure application rates versus crop yields), and to note how changes in one part change the outcome in others (*e.g.* the impact of manure application technique on N-fertilisation rate or the impact of changes in feed rations on milk yield and N in excreta).

Expert knowledge of the individual GHG-producing processes included, especially the biological processes in soil and animal rumen, will similarly ease the evaluation of model predictions of these GHG emissions and their accuracy for the system studied (*e.g.* in relation to animal production system, soil and climate conditions). Without this knowledge, there is a risk of models being used based on how user-friendly they are (Cederberg *et al.*, 2013b). In a review of whole farm system models of GHG by Crosson *et al.* (2011), it was concluded that many of the differences found in model study outcomes depend on differences in methodology and chosen emissions factors. Despite their simplicity and high uncertainty, the IPCC Tier 1 EF values are often used in whole-farm models although developed for national GHG inventories on a country level, which makes them a questionable choice for farm level studies. The frequently use of IPCC EF for soil N_2O in CF of agricultural products indicates a need for more detailed, but still user-friendly, and better performing prediction models. However, there will have to be a compromise between simple, user-friendly models and very detailed models which are complicated to run, but where uncertainty level is likely to be lower than for the simpler models. Availability of input variables is also relevant in the choice of GHG prediction models.

System analysis is another discipline of importance, *e.g.* for evaluating the choice of methodology as regards the purpose of the study and the impact that choice of FU, system boundaries and allocation methods has on the outcome. Increased co-operation between system analysts and experts in the various research fields involved in agriculture production is thus likely to improve the reliability in CF of livestock products (Cederberg *et al.*, 2013b). Based on knowledge and experience acquired during the work with this thesis, my conclusions on how the reliability of milk CF values calculated in Papers I-V could be improved are summarised in Table 8.

Table 8. *The most important measures to improve reliability in GHG estimates in milk CF, divided into epistemic uncertainty (related to knowledge availability) and variability uncertainty*

Epistemic uncertainty	Inherent variability uncertainty	
	in natural processes	in farm management at farm level
• Better prediction models for soil N_2O • Continuous update of models and parameters for enteric CH_4 models • Better prediction models for release and storage of soil CO_2 for land use and land use change • Improved statistics for roughage yields • Research on feed losses at farm level	Empirical data to improve models and increase understanding and capture variations in space and time for: • Soil N_2O measurements • Enteric CH_4 measurements for current high yielding milk production systems Improve accuracy in data on: • Roughage yields • Roughage feed intake • Total and plant available N from manure	Documentation of • Crop yields • Manure N rates/ha • Cultivation inputs and management • Feed use • Feed losses • Analysis of N in spread manure • Analysis of nutrient data for especially roughage

A crucial methodological choice of system boundary in milk CF

Besides the choice of prediction model for soil N_2O, the exclusion of CO_2 emissions from land use (LU) and LUC was presumably the methodological choice that most affected the final milk CF outcome in the present thesis. The large and varied impact that emissions from LUC associated with soy meal from Brazil alone can have on feed ration CF illustrates this (Henriksson *et al.*, 2013b; Flysjö *et al.*, 2012; 'supplementary table S5' in Paper IV). CO_2 can also be either lost from or returned to cultivated soil depending on *e.g.* crop rotation. However, including CO_2 emissions from LU and LUC can increase the uncertainty in milk CF estimates due to methodological difficulties in estimating these. As an example, *Figure 19* illustrates how different methods to assess CO_2 from LUC affect the milk CF outcome and thus the interpretation of the impact from LUC emissions on different feed rations.

Apart from the uncertainty related to quantifying CO_2 release from soil organic matter, the reversal feature of the process which both emit CO_2 and restore C in soil, makes it even more difficult to estimate. An important methodological question is how to assess and annualise changes in soil organic carbon (SOC) stocks over time. For definitive transformation of natural land (*e.g.* native forests and cerrado in South America), other crucial methodological questions are how emissions should be distributed between the products that directly or indirectly drive this LUC and the time period over which the emissions should be annualised (Cederberg *et al.*, 2009a).

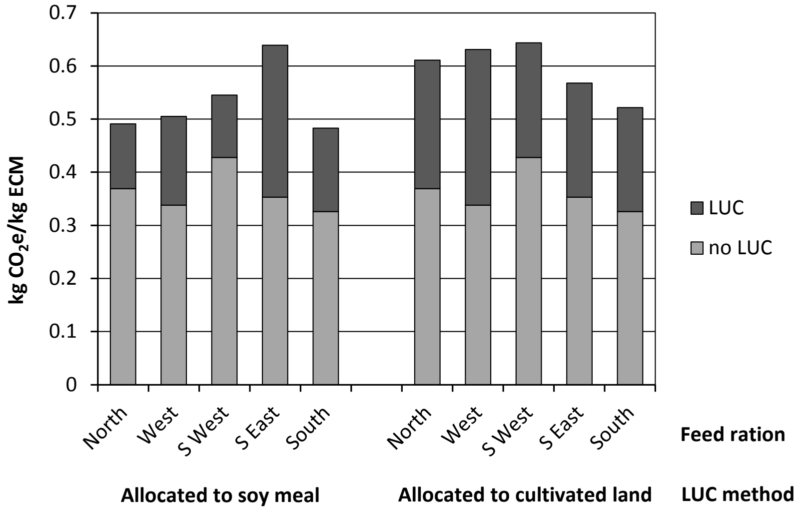

Figure 19. Greenhouse gas emissions for the life cycle of five different feed rations (Henriksson *et al.* (2014); Paper IV) on using two different methods to assess CO_2 emissions from land use change (LUC). The first method allocates LUC emissions directly to linked soy bean cultivation with the LUC factor 7.38 kg CO_2e/kg soy meal (Gerber *et al.*, 2010) (*i.e.* product-based method). The other method allocates total emissions caused by LUC to all crop production in the world with an LUC factor of 143 g CO_2e/m^2 cultivated land, assuming that the pressure for LUC is driven by all crop production (permanent and natural grasslands excluded) and thus causes LUC somewhere in the world (Audsley *et al.*, 2009) (*i.e.* land-based method).

A further problem is that one cannot state whether certain crop cultivation practices cause a net decrease or increase in SOC, as that is highly dependent on the initial SOC stocks, which will vary widely between fields due to *e.g.* cropping history (*Figure 20*). Soil cultivation practices still affect the decomposition rate of SOC, but this will be site-specific as it also depends on soil moisture and temperature.

Carbon retained in soil with one cultivation system can be lost again with another along with changes in production systems over time, which is likely to occur *e.g.* if land ownership is changed. The type of crop rotations, which are defined by the composition of feed rations, will influence changes in SOC stocks (*Figure 20*). Crop production on dairy farms consists of both perennial (grass and clover) and annual (*e.g.* grain) crops, where perennials retain more C in the soil due to more plant residues and where root growth also plays an important role for C sequestration in the soil (*i.e.* due to the longer turnover time of root C) (Kätterer *et al.*, 2012). Carbon losses are also larger in annual cropping systems, since the decomposition rate is increased by the repeated incorporation of oxygen through soil cultivation. A long-lying grass ley will thus lose SOC as soon as it is turned under for cultivation of other crops and land with annual cropping will start to sequester SOC if these are replaced by grass/clover leys.

In the majority of existing milk and beef CF estimates reviewed by Crosson *et al.* (2011), it was assumed that the soil C balance was in an equilibrium and thus changes in SOC stocks were not included. When conducting an average milk CF, as in Papers I and II, this is arguably a justifiable choice. However, in a study that compares systems which include different soil cultivation strategies, *e.g.* Paper IV, it is questionable whether excluding biogenic CO_2 emissions or C sequestration will provide a fair result. The effect of this for the results in Paper IV is that the rations which included maize silage would be expected to emit more CO_2 (or retain less) relative to those with solely grass silage, since forage maize is an annual crop with less plant residues below ground compared with perennial grass (Vellinga & Hoving, 2011). This indicates a need for common agreement on methodology for LU and LUC emissions, as well as for user-friendly prediction models.

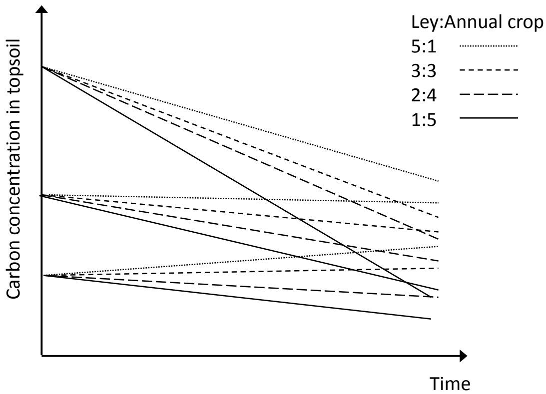

Figure 20. Conceptual illustration of the impact that initial C stock in soil and crop rotation have on C lost from or sequestered in cultivated soil (after Kätterer *et al.* (2012)).

5.1.3 Summary of uncertainties

Uncertainties in CF estimates of milk production are large and are found in the structure and parameters, as well as in the variables (input data) of prediction models for each process within the milk production chain. The level of uncertainties and its nature (*i.e.* what is causing them) differs and, due to the latter, to what level they can be reduced. To increase the reliability in milk CF, it is essential to improve prediction models for soil N_2O and SOC changes (Cederberg *et al.*, 2013b). It is also essential to use models for enteric CH_4 that are applicable for the milk production system studied. High quality data are especially important for variables to which prediction models are most sensitive, in the present thesis milk yield, animal replacement rate, feed intake, N application rates, roughage yields and feed losses.

As the crucial point for uncertainty in total milk CF is the combination of uncertainty levels and the significance that the single predicted GHG has on estimated milk CF, it is important for those conducting LCA to be aware of the different type of uncertainties in order to select accurate emissions models (incl. EF) and inventory data for the individual study. Depending on the purpose of the study, the choice of models could be more or less important, *e.g.* a differentiated model for enteric CH_4 is more important when comparing production systems with different feeding strategies (*e.g.* Paper V) than if studying the uncertainty in an average national milk CF (*e.g.* Papers I and II). Knowledge of the uncertainties in CF estimates is crucial for the interpretation of CF studies in relation to defining mitigation measures. For example, in the study of GHG emissions from production of feed in Paper IV, differences between rations were found, but it is still not advisable to draw general conclusions in the context of mitigation measures due to the uncertainties in prediction of soil N_2O and the uncertainties caused by the exclusion of CO_2 from LU and LUC. The differences found for enteric CH_4 among the feed rations compared in Paper V were even smaller and should thus also be treated with care.

Furthermore, it is crucial that policy makers and the advisory services understand these uncertainties when interpreting published milk CF estimates, which means that estimated average CF values should be published together with an uncertainty value.

5.2 Mitigating GHG emissions on the high yielding dairy farm

The overall reduction potential to reduce biogenic GHG emissions from cattle production, or agricultural production in general, is limited due to its nature. For example, ruminants are evolutionarily designed to digest feed high in cellulose, hemicellulose and lignin by a process that produce large amount of CH_4, while N mineralisation in soil is a chemical and microbial process that can be only partly controlled with farm management practices. There may also be limitations in the reduction of GHG relating to regional climate and available resources (exemplified in Papers I, III and IV). Nevertheless, there are several available measures that can be taken to promote more climate-smart milk production. In the context of mitigation measures, it is important that these are evaluated in a whole farm perspective, in order to avoid emissions saved in one part of the system leading to increased emissions in another (*e.g.* measures taken in feed ration composition to reduce enteric CH_4 can have negative effects on GHG emissions in feed production).

Reduction potential on high yielding dairy farms

The GHG reduction potential for high yielding milk production is expected to be generally lower than for production with low yielding cows (Gerber *et al.*, 2011). This is mainly explained by a generally higher efficiency of resource use in high yielding milk production systems. Due to farm management practices, variation in milk CF was estimated to be at least ±17% between Swedish dairy farms (Paper II) and approximately the same variation was found among commercial dairy farms in Denmark (*i.e.* with around 8000 kg ECM/cow and year) by Kristensen *et al.* (2011). This variation implies a reduction potential for high yielding farms, but the variation found cannot fully equal the reduction potential since it is also the result of difference in farming conditions between farms (*e.g.* climate conditions) (Paper IV).

5.2.1 Impact of milk yield per cow

Milk yield per cow plays a central role when estimating milk CF, as it is the main outcome from specialist milk production and the unit over which estimated GHG are distributed (*e.g.* kg CO_2e/kg ECM). Gerber *et al.* (2013) produce an illustrative diagram on the relationship between milk yield and GHG emissions per unit of milk in a global perspective, see *Figure 21*. It shows that the gain in saved GHG emissions by increased milk yield is marginal for milk production systems with milk yield above around 5000 kg milk per cow and year. The largest reduction potential for increased milk yield is instead in systems that yield below 2000 kg milk/cow and year.

At farm level - milk yield versus production efficiency

When estimating GHG per unit milk as in milk CF, it is logical to consider increased milk yield as a measure to reduce milk CF (Paper V). However, increased milk yield might not be the mitigation measure that should be in focus on already high yielding dairy farms. When solely aiming for increased yield per cow to reduce milk CF in high yielding herds, there is a risk that emissions could even increase, as the yield increase could induce negative side-effects on the cows, such as loss of fertility, increased incidence of disease problems and declining longevity (Oltenacu & Broom, 2010; Dillon *et al.*, 2006). It is reported that reproductive problems, lameness and other illnesses are the main reason for dairy cows to being culled in very intensive dairy production systems (Rushen & de Passillé, 2013) and also that mortality can increases with increasing herd size (Thomsen & Houe, 2006). When cow longevity declines, GHG emissions per unit of milk increase, as production efficiency declines and more replacement heifers are required. In the present thesis and in Zehetmeier *et al.* (2012), replacement heifers were found to contribute around 20% of the emissions. A side-effect of reduced replacement rate is that more of the surplus animals can be raised for meat, which will have less GHG emissions per unit of product compared with meat from pure beef breeds. The significant link between milk and beef production is discussed in a section below.

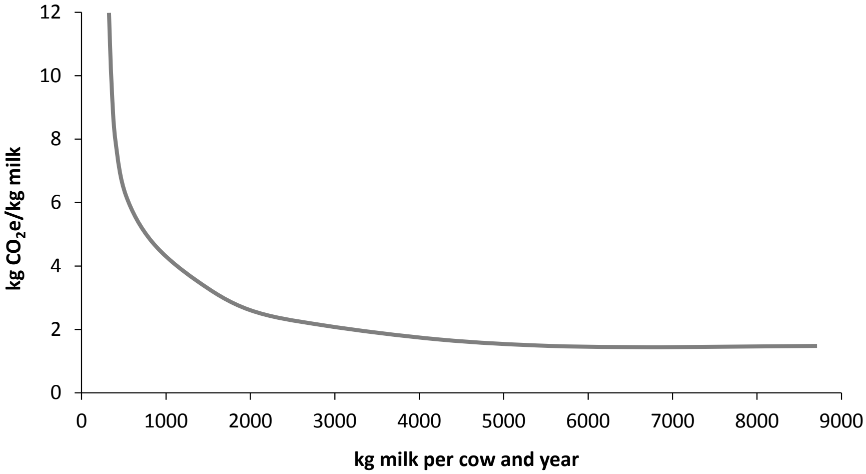

Figure 21. Relationship between greenhouse gas emissions (*i.e.* carbon dioxide equivalents, CO_2e) per kg milk and annual milk production (based on estimated country averages), after Gerber *et al.* (2011).

The effect of milk yield on milk CF is linked to the use of resources to obtain the increased yield and what this costs in GHG emissions. The marginal effect of increased input of resources to increase milk yield will decline with increasing yields. If increased yield is instead the result of improved production efficiency at herd level, reduced emissions per unit of milk can be expected and this is the situation for which the large mitigation potential at farm level is to be found (Gerber *et al.*, 2013; Kristensen *et al.*, 2011). Efficiency in this aspect involves having a high utilisation rate of resources (*i.e.* animal stock, soil, manure, purchased inputs etc.), or optimising output while minimising input. Poor use of the animal resource can, for example, be exemplified by few lactation periods per cow which means that cows are culled at a low age compared with their natural life length. Essl (1998) calculated that the economic optimum in milk production occurred at six lactations per cow 15 years ago (to be compared with the average of 2.4 in Sweden today). It would be interesting to assess where the lactation optimum for GHG emissions per unit of milk in high yielding milk production systems is today. Increased number of lactation periods equals a reduction in replacement rate and thus a notable reduction in GHG emissions (Weiske *et al.*, 2006; Paper V).

Improving production efficiency is not to be confused with increasing production intensity (*e.g.* defined as increased milk production per unit farm area or, as above, increased milk yield per cow), where the latter can increase milk CF due to *e.g.* high imports of feed (Kristensen *et al.*, 2011; Basset-Mens *et al.*, 2009b; Bleken *et al.*, 2005). It has been found that N use efficiency for the whole production cycle of milk (*i.e.* including off-farm feed production) decreases greatly when animal production is intensified using imported feed and fertilisers (Bleken *et al.*, 2005), and a higher surplus of N carries an increased risk of N_2O emissions.

Milk yield versus meat – a systems level issue

Increased milk yield per cow can lead to reduced milk CF at farm level, but it can do the opposite if the system boundaries are expanded to include the interlinked beef production. When the number of dairy cows is reduced due to increased milk production per cow, the output of meat from the dairy system will simultaneously decrease (*Figure 22*). Assuming an unchanged demand for milk and beef, increased milk yield per cow is accompanied by an increase in meat production from pure beef systems, thus leading to an overall increase in GHG emissions from the milk and beef production systems together (Flysjö *et al.*, 2012; Zehetmeier *et al.*, 2012). This is due to the larger GHG emissions per unit of meat from pure beef systems than from milk production systems (Gerber *et al.*, 2013). This was illustrated in a study of Swedish animal food production by Cederberg *et al.* (2013a), where GHG emissions per kg nationally produced beef increased from 18.0 to 19.8 kg CO_2e/kg carcass weight during a 15-year period, partly due to a strong increase in milk yield during the period (by 2000 kg ECM per cow and year between 1990 and 2005). The strong increase in milk yield was accompanied by a significant reduction in the dairy cow population and a strong increase in suckler cow numbers. The share of total national beef production derived from the dairy sector was reduced from 85% to 65% during this 15-year period (Cederberg *et al.*, 2013a).

This highly important issue should be considered in efforts to reduce the overall GHG emissions from the livestock sector, so that emissions swapping and sub-optimisation can be avoided. However, the subject has to be handled by policy makers on a national and international level. It is not a responsibility that can be addressed by individual farmers when current market forces are driving the development of the agricultural sector towards highly specialised production systems and high yields. This raises a dilemma for mitigation recommendations at farm level, where increased milk yield on one hand could reduce milk CF at farm level, but is simultaneously likely to increase the overall emissions from the livestock sector as long as demand for beef is constant or growing (*Figure 22*). This is therefore an additional reason why efforts to reduce farm-level emissions should focus on production efficiency, and not on cow milk yield, in recommendations on farm-level mitigation measures. This link between milk and meat production was not assessed in this thesis, as it would not have affected the primary aim of the studies. Instead, it was assessed in a parallel study to Paper I (Flysjö *et al.*, 2011a).

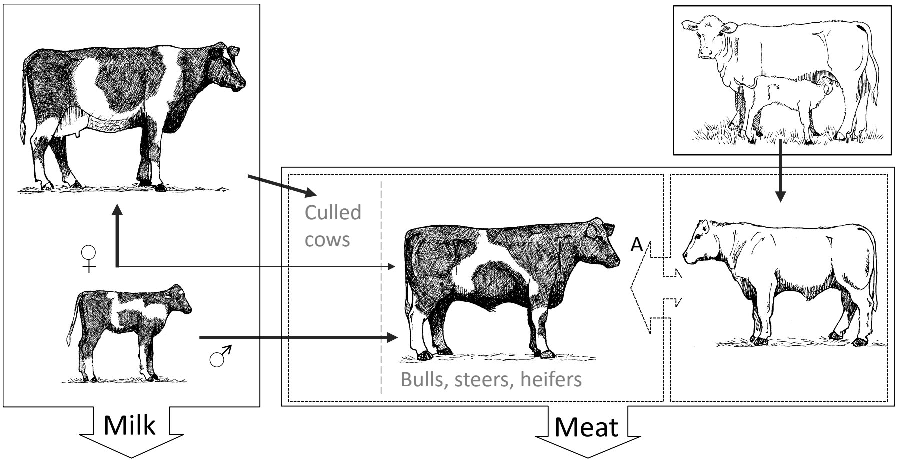

Figure 22. Illustration of the relationship between milk and meat production. Assuming the demand for milk and meat is unchanged; a reduction in the number of dairy cows (*e.g.* due to increased annual milk yield per cow) lead to an increase in the number of head and meat from pure beef production (A), while an increase in number of dairy cows also increase meat produced from the dairy system, leading to a decrease in meat from pure beef production (B). The area of the boxes in the meat output section represents the share of meat from dairy and beef production in Sweden 2005 (Cederberg *et al.*, 2009b) .

5.2.2 Impact of feed

Feed influences milk CF in several aspects, some of the most important of which are discussed below. Animal feed efficiency affects the 'milk produced:feed intake' ratio and thus how well resources are utilised (Beever & Doyle, 2007; Papers I and II). Feed production affects the CF of individual feedstuffs and, together with feed ration composition, also the CF of individual feed rations (Papers III and IV). Feeding management can also affect the total GHG emissions from milk production due to *e.g.* feed losses (Paper IV). Feed ration composition and feed characteristics affect enteric CH_4 production (Ramin, 2013; Grainger & Beauchemin, 2011; Paper V).

Feed efficiency and feed management

Since GHG emissions from feed production can represent almost half milk CF (Paper I) and vary between herds due to feeding strategy (Papers II and IV), feed efficiency is a key factor in the context of reducing emissions at farm level. Feed efficiency can be divided into two parts. One of these relates to the animal's ability to convert feed to milk or gain in weight, *i.e.* FCE (Feed Conversion Efficiency), defined as units of milk produced per unit feed DMI (Beever & Doyle, 2007). FCE is influenced by a number of factors, with feed digestibility being one of the most important (Beever & Doyle, 2007; Britt *et al.*, 2003). Besides genetic variation, FCE is closely related to farm management, as the farmer controls the quality of the feed supplied (*e.g.* digestibility and nutrient content) and the environment where animals live for feed consumption and rest, which affects animal nutrient utilisation. The impact that a change in feed DMI can have on milk CF was demonstrated in Paper I (*Figure 7*).

The other part of feed efficiency is related to the overall feed efficiency at farm level, *i.e.* the utilisation efficiency of the feed produced, and includes *e.g.* feed losses, over- or under-estimation of feed rations and replacement rate. All cultivated and harvested feeds 'cost' GHG emissions, and the smaller the feed DM losses are in the chain from field to the mouth of the animal, the less GHG emissions are unnecessarily produced. In other words, the larger the wasted feed DM, the higher the emissions load on the individual feedstuff and on milk CF.

Losses from ensiled roughage are likely to have a larger impact on milk CF than losses from grain and other concentrate feed, since DM losses from roughage are likely to be the largest as well as it is the main feed. As much as 20% of harvested grass DM can be lost during storage, according to Spörndly (2014). DM losses related to the ensiling process (storage) and during daily feeding management (feeding) (Paper III) are strongly affected by management practices (Wilkinson & Davies, 2013; Lindstrøm *et al.*, 2009). Measures taken to ensure a good ensiling process will minimise DM losses and, combined with feeding routines that result in low feed waste, will reduce GHG emissions per unit of silage fed and thus potentially also milk CF (Paper III).

The range of estimated cow FCE in Paper II indicated potential to improve feed efficiency on Swedish dairy farms. However, part of the variation found is likely explained by regional differences that can affect feed nutrient quality and ration composition (Papers III and IV). The variation would presumably also have been greater had we been able to include replacement heifers and differences in replacement rate. An inventory of individual farm FCE together with other herd performance data and feeding strategies could reveal the causes of differences in FCE between farms, and thus the potential level of improvement. At present, FCE is unfortunately not recorded in the Swedish milk recording system.

When summarising the amount of actual feed losses and feed 'lost' due to it being poorly utilised by animals, feed efficiency is likely to be an important key factor when evaluating mitigation measures at farm level. However, it is crucial to locate and identify the underlying reasons for low feed efficiency, as these will be the actual possible measures that will improve the efficiency and they can be assumed to vary between farms.

Feed production

Feed production contributes a large share of the GHG emissions from milk production (*Figure 6*). Roughage is normally produced on the farm, whereas concentrate feed is either produced on farm or elsewhere in Sweden, or is imported (the latter consists primarily of rapeseed from the EU and soy meal from South America). The ratio of home-grown to purchased feed will vary between farms for various reasons, *e.g.* stocking rate and cultivation conditions for concentrate feed. High imports of feed energy to the farm can result in higher milk CF compared with more on-farm production, according to a study of Danish dairy farms (Kristensen *et al.*, 2011). Enhanced total N input to the dairy farm via *e.g.* imported feed has also been found to significantly increase the N surplus, a source of N_2O emissions on farms (Bleken *et al.*, 2005).

GHG emissions from production of feed will partly depend on existing soils and climate conditions at the cultivation site, which make up the natural variability in feed CF that cannot be influenced by the farmer. However, emissions also depend on cultivation practices and that is where the main mitigation measures for feed CF are likely to be found.

Yield is an important factor for feed CF, as it is the functional unit over which GHG emissions are distributed, and increased yield is thus likely to reduce feed CF. An example of the yield effect was given in Paper IV: GHG emissions from high yielding barley (8.2 Mg/ha) were 0.315 g CO_2e/kg DM, compared with 0.388 g CO_2e/kg DM for lower yielding barley (3.3 Mg/ha). However, these differences are also caused by other management practices and cultivation conditions, exemplified with grass/clover silage in Paper III. Increased yield will also have an indirect effect on the limited resource of available cropland (since high yields require less land). For example, in Paper IV cultivation of horse bean required twice as much land area per kg DM as grain, due to lower yield. Crop yield can be increased by optimising growing conditions through *e.g.* low soil compaction, optimal pH and good drainage, measures that will also have the combined effect of reducing the risk of soil N_2O emissions (Hénault *et al.*, 2012; Simek & Cooper, 2002).

The amount of N applied to soil will have a direct effect on soil N_2O emissions but also an indirect effect, since N fertilisation rate is strongly correlated to crop yield. It is thus important to make requirement calculations for N application rate in relation to expected crop yield, so that the N dose is not excessive. When input of synthetic N-fertiliser was increased by 10% in Paper I (*i.e.* barely 10 kg/ha on average), this increased the overall Swedish milk CF by around 2%. In a national study of N-fertiliser rates to winter wheat from over 4000 fields, it was revealed that 30-40 kg more N/ha than required were commonly applied (Stenberg *et al.*, 2005). Surplus N from synthetic fertiliser also 'cost' GHG emissions to produce. On the other hand, if N application rates are initially too low to allow the production potential of the cultivated land to be achieved, increased N rates can increase yield and thus reduce GHG emissions per unit crop. In a longer-term perspective, an increase in yield can also mean that more C is restored in soil (*e.g.* with plant residues), resulting in lower net soil emissions of CO_2 according to Kätterer *et al.* (2012).

The management strategy employed for manure application will affect feed CF, since increased utilisation efficiency of applied manure N will reduce the need for synthetic N-fertiliser. Reducing NH_3 emissions and NO_3^- leaching due to well-managed manure application (*e.g.* choice of application techniques and application time) will also reduce indirect emissions of soil N_2O (Petersen *et al.*, 2013). The impact of manure application practices was not studied in this thesis, but the interesting finding of a lack of the expected correlation between stocking rate and N-fertiliser rate for 1000 Swedish dairy farms implies that the potential exists to reduce GHG emissions by improving manure utilisation (Paper II). Similar results have been found for a large number of European dairy farms, where large feed imports to the farm increased the import of other N supplies to the farm instead of the opposite, as would have been expected with efficient use of manure N (Bleken *et al.*, 2005).

Use of fossil fuel for field operations and the machinery used for processing and feeding roughage silage cause CO_2 emissions which constituted around

33% and 20% of grain CF and grass/clover silage CF, respectively, in Papers III and IV, although large variations between farms can be expected (Paper II). Lowering the use of fossil fuel will have a positive impact on milk CF and can be achieved by reduced tillage. However, reduced tillage practices can increase soil N_2O emissions on poorly aerated soils (Rochette, 2008), so these types of measures have to be individually evaluated at farm level.

Crop rotation characteristics can affect crop yields and the SOC balance (*Figure 20*) and thus indirectly the feed CF, which is explained by *e.g.* the effect that different crops and crop combinations have on soil fertility. For example, perennial crops and crops with deep root systems generally have a positive effect on soil structure, which provides good growing conditions.

An interesting combined effect of yield, N-fertiliser, number of cuts and field operations was found for production of grass/clover silage (Paper III). When an additional grass cut was made to obtain higher nutrient quality silage, this resulted in increased GHG emissions per kg DM of silage. This was the result of the N and fossil fuel used for the extra cut, which increased the total amount of N and fuel, whereas the total grass/clover yield remained the same regardless of whether three or four cuts were made. However, Paper III showed that yield needs to increase in a four-cut system compared with a three-cut system to avoid increased GHG emissions per kg DM. The knowledge of yield levels in a four-cut system compared with a three-cut system is limited. Grassland advisors consulted for the study could not report a general increase in total yield based on their practical experience. In a previous study comparing yield from two or three cuts (n=6) and three or four cuts (n=2) in field trials, the extra cut reduced the DM yield by 3% and 5%, respectively (Gunnarsson *et al.*, 2014). The benefit of higher quality silage is to lower production of enteric CH_4. However, this effect was marginal (on average 2% reduction) when estimated in Paper V and could not fully compensate for the increase in GHG emissions from producing the higher quality silage (*Figure 16*). Thus more knowledge and experience from field trials regarding this aspect is needed before suggesting an extra grass cut as a measure to reduce milk CF at farm level.

Another aspect of yield relating to nutrient composition in feed rations concerns forage maize. Although forage maize can be cultivated up to about 60ºN in Sweden, yield and nutritional quality decrease with increasing latitude (Mussadiq *et al.*, 2011) and the differences between emissions per kg DM for maize and grass silage will thus be site-specific.

To summarise, feed CF can be improved by increasing N use efficiency, optimising crop yield, improving soil fertility and minimising input resources. The GHG emissions from grass or maize silage production are especially important to evaluate in relation to yield level, nutrient quality, input of N and fossil fuel and impact on enteric CH_4 production. Due to the prevailing conditions for crop cultivation, each farm will have individual limitations in the improvement of feed CF.

Feed intake and enteric methane

Amount of feed DMI is strongly correlated to amount of enteric CH_4 produced, explaining 85% of the CH_4 emissions according to Ramin and Huhtanen (2013). Feed nutrient composition also affects CH_4 production, with high starch content (*i.e.* due to increased production of propionate) and increased fat content in the ration lowering the production of enteric CH_4 (Grainger & Beauchemin, 2011). High starch content can be achieved by increasing the concentrate shares (grain) or by the use of maize silage. Increased proportion of roughage is generally known to increase enteric CH_4 production due to its higher fibre content and lower digestibility, and thus slower passage through the rumen compared with concentrates (Johnson & Johnson, 1995). However, Patel *et al.* (2011) showed that increased share of roughage is not necessarily followed by increased CH_4 if high quality grass silage is used. When roughage quality is changed, the proportion of roughage and concentrate can also be expected to change. In the present thesis, increased roughage quality led to increased proportion of roughage (partly as it is an economically preferable feedstuff and handled as such by NorFor optimisation) and reduced concentrate share, with an overall decrease in DMI and thus also in enteric CH_4, despite the increased proportion of roughage (Paper V).

The impact that feed ration characteristics have on enteric CH_4 production requires the use of differentiated prediction models for studies assessing the impact of feed ration on milk CF. However despite this, prediction models can estimate differently, *e.g.* when evaluating a ration with increased share of high quality grass silage, the default model used in Paper V estimated a reduction in enteric CH_4 production, whereas another model estimated the opposite. The use or increase of certain feedstuffs to reduce enteric CH_4 production also needs to be evaluated for GHG emissions during the production of that feedstuff, as discussed in more detail below.

Feeding strategies and the impact of different feedstuffs

The overall GHG emissions from animal diets, referred to as ‘ration CF’, depend on the CF of the individual feedstuffs and the proportion of these different feedstuffs in the ration (Paper IV). The latter is highly influenced by the nutritional requirements of the animal and the nutritional and economic characteristics of the feedstuffs. Different feedstuffs can also be included in rations for a particular reason. This can be to reduce enteric CH_4 production by including feedstuffs rich in starch (*e.g.* maize silage) and fat (*e.g.* rapeseed) or reduce GHG emissions from cultivation (*e.g.* N-fixing legumes) or transport (*e.g.* regionally produced feed).

Roughage is generally the feed component that influences ration CF most, as it constitutes the largest part of herd feed intake (around 50%), whereas minerals and lime will have a marginal impact, as their share in rations is very small (Paper IV, *Figure 11* and *12*). Grass from grazing will have a small impact on ration CF in production systems where it contributes a small part of feed DMI (*e.g.* in Sweden). Roughage nutrient quality affects ration composition since it is the feed component that regulates the nutrient composition in the complementary concentrate feed, as illustrated in Paper IV with two different silage qualities (*Figure 11*).

Ration composition will also depend on feed availability on the individual farm due to regional cultivation conditions (*e.g.* climate, soil type, latitude *etc.*) and the availability of by-products from food industries (Paper IV).

The impact that inclusion of a single feedstuff can have on ration CF depends on its relationship to the feedstuff it is intended to replace and how this changes the overall composition of the ration. Accordingly, it is important to assess the overall ration CF when evaluating mitigation measures instead of just including feedstuffs that have a low CF or are assumed to have a reducing effect on enteric CH_4 emissions.

<u>Soy meal</u> is a commonly used protein source in Swedish dairy rations, constituting on average around 8% of dairy cow intake of crude protein (around 220 kg soy meal per cow and year in 2010 (Swedish Board of Agriculture, 2011a). Due to increased market prices, use of soy meal has declined from much higher levels (around 33%) in the last 10 years. Brazilian soy meal (the main type used in Sweden) is associated with GHG emissions from LUC, but the magnitude of these is highly uncertain and there is currently no consensus on methodology for including LUC emissions in LCA and CF studies (see last part in section 5.1.2 and *Figure 19*). How soy meal affects ration CF will thus depend strongly on the methodology used to estimate emissions from LUC and also on the origin of the imported soy, as the CF of soy meal differs depending on where it is grown (Flynn *et al.*, 2012). How ration CF is influenced by soy meal will also depend on the CF of alternative protein crops that can replace soy meal. The origin of soy meal and its share in

commercial protein concentrate and compound feed will differ between products and, due to market prices, over time.

Domestically grown protein crops are *e.g.* rapeseed meal and horse bean. Comparing these with soy meal, horse bean was estimated to produce almost half the GHG emissions per kg DM compared with the others (emissions from LUC excluded). However per kg crude protein (CP), soy meal had less than 10% greater GHG emissions than horse bean and when comparing emissions related to protein quality, soy meal had 8% and 35% lower emissions per g AAT_{20} (amino acids absorbed in the small intestine, defined by Volden (2011)) than horse bean and rapeseed meal, respectively (Henriksson *et al.*, 2013b). Consequently, the protein sources used will affect the proportions and inclusion rates of other feedstuffs in the ration and thus ration CF. Horse bean can have a positive effect on ration CF, but the effect is also related to yield level and this decreases with latitude, as does the maturation time, making time of harvest unpredictable. It also has to be noted that the lower emissions come at the cost of greater land use (*Figure 12* and *13*, West region).

The CF of commercial concentrate products can be expected to vary due to the CF of the ingredients included. Among the products assessed in Paper IV, compound feed including grain (30-50%) had on average a lower CF (410-650 g CO_2e/kg DM) than pure protein concentrate (520-730 g CO_2e/kg DM). The difference was a combined effect of the CF of individual ingredients (incl. transport to feed factory) and their relative proportions in the ration. Grain can have different CF depending on site of production (Wallman *et al.*, 2011; Paper IV). The share of soy meal content in these products had no correlation to the product's CF, implying that the protein source is not crucial for the product's CF (Henriksson *et al.*, 2013b). The choice of commercial concentrate or compound feed as a measure to reduce ration CF is limited at farm level, as these products are selected to balance the amounts and content of nutrients in roughage and other predefined feedstuffs and also as the product CF is likely to change over time due to changes in feed formulations (by the feed industry) caused by availability of ingredient and market prices.

Maize silage can have a positive effect on ration CF as it can be cultivated with less GHG emissions per kg DM than grass due to higher DM yield/ha. The maize silage used in one of the rations assessed in Paper IV was estimated to have 60% lower emissions per kg DM than the regional grass silage, and thus contributed to keeping the overall GHG emissions low. In the situation studied, grass yield was however relatively low due to regional dry conditions, which explains this large difference between estimated GHG emissions per kg DM maize and grass silage. Maize silage has also been shown to lower production of enteric CH_4 due to its high starch content. However, a reduction in estimated enteric CH_4 could not be observed in the comparative study of rations in Paper V (*Figure 15*, S East region), presumably as the enteric CH_4 prediction model was not differentiated for starch content and as the overall nutrient composition of a ration is a mixture of all feedstuffs included. As the S East region had favourable conditions for forage maize cultivation, it had a reducing impact on the overall ration CF (Paper IV). As also pointed out earlier, geographical location and cultivation conditions seem crucial if maize silage is to have an reducing effect on overall milk CF. A disadvantage of forage maize cultivation is its negative impact on SOC as it is an annual crop with less plant residues below ground (Kätterer *et al.*, 2012). Thus, the positive effect found for forage maize in ration CF in Paper IV is likely to be reduced since cultivation of an annual maize crop presumable causes more soil CO_2 emissions compared with cultivation of perennial grassland crops (Vellinga & Hoving, 2011), however not captured in the results due to the exclusion of soil CO_2 emissions.

By-products from the food industry, *e.g.* dried beet pulp from the sugar industry and dried distiller's grain, can be expected to have quite low CF (around 250 g CO_2e/kg DM; Paper IV) compared with other feedstuffs, as the emissions are mainly allocated to the main product. Thus, animal edible by-products from food industry are an important measure for the overall livestock sector as it has a reducing effect on emitted GHG. The availability of by-products is however limited to a quantity defined by the production of the main crop. Unless there is an unused surplus of the by-product, using it as a mitigation option to reduce GHG emissions at farm level will only be a shift of emissions between farms.

It has to be borne in mind that the estimated CF of different feedstuffs is not constant. As already discussed here, it varies due to *e.g.* crop cultivation conditions and practices (as for grass silage in *Figure 14*), but can also be expected to vary due to estimation methodology. In this thesis, for example, grass/clover silage was generally found to have larger GHG emissions per kg DM than grain (on average 20%), while the opposite was reported by Flysjö *et al.* (2008) and Wallman *et al.* (2011). This can be explained by differences in input data, *e.g.* yields per ha and number of grass cuts. It is thus crucial not to use published CF values of individual feedstuffs in estimates of ration CF or milk CF calculations without ensuring that they represent conditions representative for the situation studied, especially for feedstuffs that comprise a significant share of the ration.

To summarise, the complexity in ration composition and the variation in the CF of individual feedstuffs make it difficult to define general recommendations for reducing GHG emissions at farm level by feeding strategy. The use of a particular feedstuff as a reduction measure (*e.g.* maize silage) needs to be evaluated in a whole ration context and on a regional or farm basis, *i.e.* GHG emissions from both feed production and enteric fermentation. However, the use of food by-products is likely to have a general reducing effect on GHG emissions per kg DM. The impact of feedstuffs on the overall ration CF will be influenced by the quality of nutrients in the individual feedstuffs, *e.g.* protein quality varies between feedstuffs and thus *e.g.* 1 kg CP from soy meal cannot be replaced by 1 kg CP from horse bean or grass/clover silage.

5.2.3 Other impacts

Manure

GHG emissions derived from stored manure also contribute to the overall GHG emissions from milk production. However, these were not specifically targeted in the context of mitigation measures in the present thesis, since they contribute a smaller amount to overall milk CF than enteric CH_4 and GHG emissions from feed production. CH_4 emissions were estimated to contribute around 3% and N_2O, mainly indirectly from volatised NH_3, around 2% (*Figure 6*; Table 4 in Paper I). However, there are measures to be taken in this context of manure management, *e.g.* putting a solid cover on slurry, lowering the pH in slurry by additives and anaerobic digestion of manure can reduce emissions (Petersen *et al.*, 2013).

Energy and transport

CO_2 emissions from energy use, excluding energy for field operations, constituted 5% of overall milk CF (which was twice as high as for the grazing-based system in New Zealand) (Paper I). Of these emissions, 20% came from electricity (milking and cooling) and the majority of the rest from transport and processing of feed. However, there is most likely variation between farms and reducing energy use can be a reduction measure, among others, at farm level. The low impact from electricity is explained by low emissions from the main energy mix used in Sweden, which is based mainly on nuclear and water power. In regions where energy is based more on fossil power, as in many other European countries, the impact of electricity on milk CF will be larger.

The impacts of feed transport from feed factory to farm depending on transport differences were estimated in Paper IV. GHG emissions from long-distance transport (300 km one-way) of all concentrate (compound feed incl.

grain) contributed 3% of ration CF, while a shorter transport distance (100 km one-way) of only protein concentrate (*i.e.* if grain produced on-farm) contributed <1% of the emissions (background data for Paper IV).

5.2.4 Summary of mitigation measures

It is crucial to assess mitigation measures on a whole-farm basis in order to avoid swapping emissions between the various parts of the milk production chain, as exemplified by the feed ration effect on enteric CH_4 emissions and emissions from feed production. It is also important that the use of individual feedstuffs is evaluated in a feed ration perspective.

Some mitigation measures can be recommended as general while others need to be evaluated at farm level (*Table 9*). General measures are *e.g.* overall increased production efficiency, feed conversion efficiency and N use efficiency in feed production (note that efficiency in this context is not equivalent to intensified production). In addition, a side effect of optimised utilisation of resources is likely an improved economical outcome. Other measures that are influenced by regional or site-specific conditions can have either a positive or negative effect and thus need to be evaluated at farm level in order to find the most effective measures (as well as the most economically viable). However, this will require the advisory services to have both broad and deep knowledge of GHG emissions from the various parts of the milk production chain.

Using increased milk yield as a measure in already high yielding milk production has to be treated carefully, as the effect can be the opposite if it influences cow health and longevity negatively. Increased milk yield per cow also risks increasing the overall GHG emissions from cattle production, *i.e.* milk and meat, but this is primarily an issue for policy makers to solve.

In the context of feeding strategies, the potential to reduce GHG emissions is presumably largest for measures taken in feed production, compared with the impact that changes in feed ration have on enteric CH_4 production. To reduce feed ration CF, important measures are those relating to N use efficiency, manure utilisation and soil fertility.

Table 9. *Mitigation measures to reduce greenhouse gas (GHG) emissions at farm level in high yielding milk production systems*

General recommendation	Evaluated for the individual farm
Improve production efficiency	Milk yield
Optimise utilisation of resources	Changes in feed ration composition
Reduce replacement rate	*Use of special feedstuff*
Increase cow longevity	*On-farm production of special feedstuffs*
Improve feed conversion efficiency	GHG reduction measures in crop cultivation
by feed quality and animal health	Improve nutrient quality in grass/clover silage
Reduce feed losses	*Management strategies*
in storage and by feeding management	
Reduce GHG emissions from feed production	
by N use efficiency and manure utilisation	
by improving soil fertility	
Use by-products from food industry as feed	

5.3 Influence of uncertainties in CF estimates on farm-level mitigation

The large uncertainties in milk CF estimates will have consequences when these are used to assess mitigation measures. It is thus reasonable to ask how well current CF calculations for milk production can serve as a tool for mitigation measures at farm level. Undoubtedly, the life cycle perspective is necessary to avoid sub-optimisation. However, in view of the simplicity in many commonly used emissions models predicting GHG, combined with the complexity in the biogenic processes contributing the majority of these GHG emissions, use of milk CF estimates as a tool for individual farm-level mitigation can be regarded as somewhat questionable. This is not to say that CF estimates should not be used, but calculated results need to be carefully interpreted due to the uncertainties in the prediction models used. When better prediction models can be used, CF estimates can also be a more useful tool for farm-level mitigation.

The problem is that many prediction models are not detailed enough to capture all farm management practices with effects on GHG emissions, especially for soil N_2O and soil CO_2 but also enteric CH_4 emissions. As an example there are cultivation practices apart from N application rate that are well known to affect soil N_2O emissions, *e.g.* lowering soil compaction, drainage and timing of N application (e.g. Hofstra & Bouwman, 2005). The impact of CO_2 emissions from LU or LUC is also highly uncertain due to site-specific impacts such as soil characteristics and climate, and the various ways to predict it (e.g. Flysjö *et al.*, 2012). To evaluate changes in feed ration composition to reduce enteric CH_4, prediction models need to be differentiated for nutrient composition, thus data on feed characteristics also need to be available. To summarise, mitigation measures revealed from empirical studies of specific processes in the milk production chain, *e.g.* N_2O from cultivated soils (see section 2.2.1), are also important for the reduction of GHG emissions at farm level, although they might not be detectable in milk CF estimates.

Input variables are also influenced by uncertainties and variations and it is thus crucial that model input data actually reflect the conditions studied. Important variables in this regard are *e.g.* data on crop yield and fertiliser rates. Feed intake is another important variable, especially for roughage, which is often fed *ad libitum*, as it defines GHG emissions from both feed production and enteric fermentation. It is also important that feed losses from roughage are accounted for in milk CF estimates.

5.3.1 Some aspects of farm-level guidance to reduce GHG emissions

It is vital in a guidance context that farmers get an understanding of the overall picture of GHG emissions from milk production, *e.g.* where the different sources of GHG emissions are, the magnitude of the emissions from different farm activities and where the potential for reductions lies. CF estimates can provide a useful tool in this regard, since uncertainty levels are then of minor importance. CF estimates can also serve as a tool to evaluate mitigation measures such as changes in feeding strategy that lead to changes in cultivation, although the approach is limited as regards detecting individual farm mitigation measures and following up changes in GHG emissions after implementation of measures.

Another notable aspect of CF estimates conducted in a farm-level guidance perspective is how the time boundaries are drawn. Many activities on the farm occur at different times of the year, which means that *e.g.* milk production in one year is partly based on the previous year's feed production and that manure produced in one year is spread in the next. Thus, when calculating actual activities and production results for a calendar year, it is likely that emissions are displaced between years.

Producing a detailed and site-specific milk CF is an extensive and highly time-consuming process that also needs good knowledge of the topic. This requires the use of complementary ways to detect and follow up the results of implemented mitigation measures in farm-level guidance. Key indicators can be a valuable tool in this regard for detecting the efficiency of resources. One significant key indicator can be FCE (feed conversion efficiency), which relates milk output to feed intake (section 5.2.2). Others can be replacement rate, N efficiency, farm N surplus and milk losses. Olesen *et al.* (2006) found a significant relation between increase in farm N efficiency and reduced GHG emissions per unit of milk. Some of these variables are easily available to farmers through the milk recording system or crop cultivation schemes, while others need further documentation at farm, *e.g.* crop yields. Efficiency in the production of grass silage could be checked with *e.g.* silage DMI/ha temporary grass and N application rate/unit grass silage fed, but this requires some weighing work and DM analysis. The advantage with key indicators is that they can give more refined images of how management practices affect e.g. herd performance, manure utilisation and energy use. They can also allow faster detection and follow-up of farm-level mitigation measures than milk CF estimates. A national study on using key indicators in farm-level guidance has recently been performed by Berglund *et al.* (2014) with the aim to develop farm level guidance for mitigating GHG emissions. The use of key indicators will however also need defined ranges for optimal values, which are not currently available, and thus further inventory of how defined indicators relate to farm-level GHG emissions is needed.

The overall recommendation based on the work in this thesis is that CF calculations at farm level should mainly be used initially to provide an overview of the sources and magnitude of the farm's GHG emissions. Key indicators could then be used, as an important tool for both detecting and following up on farm-level mitigation measures. Furthermore, not all mitigation measures affecting GHG emissions at farm level can be detected or magnified either by CF estimates or key indicators, especially those that have a more indirect effect, *e.g.* improved soil drainage to reduce the risk of N_2O production, a measure more or less impossible to detect or quantify at farm level.

The overall reason for guiding dairy farms to reduce their GHG emissions is to contribute to the overall reduction in anthropogenic GHG emissions, at least emissions from the livestock sector and not to achieve as low milk CF as possible at the individual dairy farm. In this regard, an important issue is how to manage the interlinkages between milk and meat production and how to communicate mitigation measures that can be contradictory depending on the level at which they are evaluated (farm, national or global). How can we achieve the goal of reducing GHG emissions per unit of milk produced without simultaneously increasing the overall emissions from the livestock or agriculture sector? This is a crucial question for farm-level recommendations to reduce GHG emissions.

5.4 Other aspects of environmental impacts and sustainable cattle production

Greenhouse gas emissions are just one of a number of environmental problems that can be ascribed to agricultural activities, but are of great importance due to the current severe situation with increasing global warming. Since GHG emissions disperse in the atmosphere, irrespective of the site of emission, they are a global issue, whereas other pollutants mainly have a regional or local influence, *e.g.* eutrophication, acidification and toxicity caused by pesticide use.

Environmental problems have to be viewed in relation to the benefits human society and the ecosystem derive from cattle production. Ruminants have the ability to produce nutritionally valuable food products from plants rich in hemicellulose, cellulose and lignin, such as grass, which are inedible to humans and which can be grown in conditions and soils not suitable for food crop production. Perennial roughage crops in rotation with food crops are also beneficial for soil fertility and can reduce nutrient leaching causing eutrophication. Other crucial benefits of cattle farming are recycling of nutrients by manure to soil and plants, preservation of biodiversity in grazed habitats, provision of livelihoods for many people and, especially in poorer countries, a source of economic capital, transport and draught power. Livestock also constitute an essential part of human culture since they were first domesticated and contribute aesthetically to the landscape, although these benefits are more subtle and difficult to evaluate (Janzen, 2011).

In order to take advantage of all these benefits in a world where the demand for dairy and meat products is predicted to grow, it is essential to develop sustainable methods for meat and milk production so that negative side-effects can be avoided. As been pointed out by Janzen (2011), this might require new ways of thinking when measuring and evaluating systems and their products, *e.g.* the human diet could be the functional unit studied instead of single food products (van Hooijdonk & Hettinga, 2013).

The potential to reduce GHG emissions in Swedish dairy production is marginal when viewed in a global perspective, due to a combination of Sweden's low contribution to world milk production and its high yielding dairy industry, which results in low emissions per unit of milk produced (*Figure 21*). However, this does not excuse inactivity in mitigating GHG emissions from Swedish milk and meat production, especially since as discussed above, the high yield in the milk production system decreases the availability of dairy-based meat, resulting in increased demand for cattle meat from pure beef breeds, both nationally and internationally produced (Cederberg *et al.*, 2013a;

Flysjö *et al.*, 2012). This result in more GHG emissions than what would be the case with meat from dairy or dual-purpose breeds (Gerber *et al.*, 2013; Zehetmeier *et al.*, 2012). In another perspective, this can make Swedish high-yielding milk production questionable.

When evaluating the contribution of GHG emissions and other environmental impacts between products, it is reasonable to do so in a way that takes account of the product's significance for human survival. Although agricultural activities contribute great amounts of GHG emissions, they also provide food for our survival and thus these emissions should be accepted as more necessary side-effect than emissions derived from consumption of unnecessary capital goods and transport. The nutrient content in food products is another aspect to consider when comparing GHG emissions costs for food products. This was done in a previous study comparing beverages with different nutrient density, where milk had a substantially higher 'Density to Climate Impact' index than *e.g.* soft drinks, juice and beer (Smedman *et al.*, 2010).

The responsibility to reduce the GHG emissions load from milk and meat production, as well as from other agriculture food products, is collective. Major responsibility rests also on the consumers, individuals as well as communities, and on retailers and policy makers. An important aspect is the large quantities of food waste, especially in developed countries, partly driven by a combination of high income and low food prices, *i.e.* many people can afford to throw away food. Today, around one-third of the edible food produced is estimated to be lost or wasted. The level of waste *per capita* is largest in Europe and North America, where a large proportion occurs at consumer level, *e.g.* an estimated 50% of losses and waste for milk and meat (Gustavsson *et al.*, 2011). This means that measures taken by farmers to reduce GHG emissions per unit of milk produced at farm level are easily negated by *e.g.* a discarded glass of milk or other dairy products wasted. Thus, we all have a responsibility to contribute to a reduction in GHG emissions from food production. Reducing food waste, especially of products with high emission loads such as dairy and meat products, is just as important a mitigation measure as those taken at farm level.

6 Conclusions

Greenhouse gas emissions from milk production mainly take the form of CH_4 from enteric fermentation and N_2O and fossil CO_2 from feed production (i.e. N_2O from soil and production of synthetic N-fertiliser and CO_2 from field operations and N-fertiliser production). For Swedish milk production (i.e. a high yielding system with confined animal feeding and a large share of concentrate), these GHG (as CO_2e) were found to contribute 46% (enteric CH_4) and 41% (feed production, 28% as N_2O and 13% as CO_2) to total milk CF in this thesis. All GHG contributing to total milk CF were distributed as CH_4 50%, N_2O 32% and CO_2 18%.

Uncertainty

There is large uncertainty in GHG estimates of milk, as more than two-thirds of the emissions are approximated to be biogenic CH_4 and N_2O produced in complex and varying biological processes in nature. Thus, these emissions are difficult to predict without fairly large uncertainties. Here, this uncertainty was assessed to be approximately ±30% of the GHG estimate for Swedish milk. The milk CF was mostly influenced by the emission factors for enteric CH_2 and N_2O from soil and the variable ‘feed dry matter intake’. If biogenic CO_2 from land use and land use change would have been included the uncertainty is likely to have been even larger.

Uncertainties in average milk CF estimates are also caused by the large variation in the input data used to characterise the milk production system (*e.g.* a national average or a specified production systems) due to variations in management practices and biological outputs (*e.g.* milk and manure) among dairy farms.

The large uncertainties relating to GHG estimates of milk indicate that

- Milk CF values should not be compared unless they have been estimated in a comparable way (*i.e.* with the same prediction models for biogenic GHG, same system boundaries, same allocation methods *etc.*)
- Milk CF values should be communicated with uncertainty intervals and studies of GHG estimates should be published with high transparency regarding calculation methods and input data
- Caution is needed when milk CF studies are conducted or interpreted to define mitigation measures.

To obtain more valid and reliable milk CF estimates, it is essential to improve prediction models for biogenic GHG, especially for soil N_2O and changes in SOC stocks, and to use high quality input data for variables to which prediction models are most sensitive, *e.g.* milk yield, feed intake (especially roughage), animal replacement rate, N application rate, roughage yield and feed losses.

Mitigation

The variation in estimated GHG emissions found here between individual high yielding Swedish dairy farms, that were at least ±17%, indicates that there is potential to reduce GHG emissions from high yielding milk production, both on a national level and on individual farms. Some mitigation measures can be presumed to be generally applicable, while others need to be evaluated on a farm or regional level, as their effects on GHG emissions are influenced by regional or site-specific conditions.

General mitigation measures relate to efficient use of resources (which is not synonymous with intensified production) and include:

- Increased overall herd production efficiency
- Increased feed conversion efficiency
- Increased N use efficiency in feed production
- Increased efficiency in grass cultivation with retained or increased nutrient quality
- Reduced feed DM losses in storage and at feeding
- Utilisation of by-products from the food industry if available.

Mitigation measures that need to be evaluated at farm level, as they presumably differ in effectiveness and may have opposing effects due to local conditions, include:

- Increased milk yield per cow
- Changing feed ration composition by inclusion of special feedstuffs, as it can have opposing effects on enteric CH_4 emissions and GHG emissions from feed production
- Measures to improve crop yield, which generally reduce feed ration CF, as critical evaluation is needed if yields are improved by increased N application rates, since this increases the risk of increased emissions
- Measures to reduce silage CF are especially important, since silage comprises the largest part of dairy herd feed rations
- Measures in crop cultivation practices that best reduce the risk of soil N_2O production, which will vary individually between farms.

Increased milk yield as a measure to reduce milk CF has to be treated carefully, especially as it is also likely to increase the overall GHG emissions from the livestock sector when beef production is considered. Changes in feeding strategy can be expected to have a larger influence on GHG emitted from feed production than on CH_4 from enteric fermentation.

Farm-level guidance

In the work of guiding individual farms to reduce their GHG emissions, identification of key indicators will be an important complement to milk CF estimates including large uncertainties and are extensive, time-consuming and expensive to conduct at the necessary level of detail for individual farms. Key indicators are likely to be more detailed in the detection and evaluation of mitigation measures. Milk yield and feed intake are two of the most influential parameters in milk CF estimates, and thus feed conversion efficiency (*i.e.* units ECM produced/unit DMI) can be a useful key-indicator of the GHG reduction potential on the individual farm.

7 Further research

Uncertainty

Further research is needed to reduce the uncertainties and improve the reliability in GHG estimates of milk. Crucial issues are:

- To improve user-friendly (*i.e.* in a LCA perspective) prediction models for biogenic GHG emissions, especially for soil N_2O and CO_2 emissions from SOC changes
- Methodology to include emissions relating to cultivation changes in agricultural and native land, *i.e.* how to annualise and allocate the reverse process of biogenic CO_2 emissions
- To improve accuracy in input data, especially for yields of forage crops and feed losses
- To update national data on above- and below-ground plant residues used when estimating soil N_2O
- To initiate collaborations between experts in the different fields emitting GHG in the milk production chain and researchers working with environmental assessments.

Mitigation

More knowledge is needed on mitigation measures at farm level in a regional perspective, as pre-defined conditions will influence the effect of different measures. This will require:

- Further studies on the influence of feeding strategies on emissions from feed production that also include SOC changes, especially the influence of perennial and annual forage crops

- Further studies on how changes in dairy cow replacement rate influence the overall GHG emissions from milk production, connected with its effect on overall herd productivity
- National studies that can distinguish and map specific mitigation measures for various farm types in different locations
- National studies that can connect variations in milk CF (as found in Paper II) with differences in farm management practices
- Define and evaluate key indicators that can be used to identify and evaluate mitigation measures at farm level
- Empirical studies on the relationship between such indicators and GHG emissions in order to define optimal ranges for each indicator.

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