Analysing the Carbon Footprint of Food

Insights for Consumer Communication

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Abstract

In Europe, food consumption is responsible for approximately 30% of total greenhouse gas (GHG) emissions. There has been huge interest in estimating the carbon footprint (CF) of food products, *i.e*. the total amount of GHG emitted during the life cycle of the product, and communicating these to consumers to enable them to make informed choices. This thesis provides additional knowledge of several related issues regarding calculating and acting on the CF of food products in order to facilitate the design of effective consumer communication strategies. The uncertainty in the CF of Swedish potatoes and pasta was established to investigate the detail to which food CF can be determined. For a well-defined geographical area the uncertainty was in the range ±10-30%, indicating that the CF uncertainty for more complex foods or foods with a more unspecific origin is considerably higher. Emissions of N_2O from soils dominated the emissions and uncertainties, and yield was an influential parameter for all crops. Possible risks of pollution swapping when acting on CF were investigated in the case of meat production. For meat from monogastric animals, in most cases the CF functions as an indicator for land, energy and pesticide use, and for acidification and eutrophication potential, but for ruminant meat there are possible conflicts with biodiversity, energy and pesticide use. In an attempt to develop a tool that communicates the CF of meat in an efficient way, while highlighting important trade-offs, a criteria-based meat guide based on the knowledge gained was developed. A critical review of CF labelling from a consumer perspective showed that obstacles known to prevent purchase of organic foods, *e.g*. perceived high price and strong habits, apply equally or more so to the purchase of CF labelled foods. Hence, CF labelling of food in a retail setting is of limited effectiveness, but CF values are important in business-to-business communication, in policy development and for developing efficient and scientifically justified consumer communication messages. Quantification of the reduction potential from a commonly recommended option, 'eating seasonal', showed that consuming tomatoes and carrots seasonally in Sweden could reduce the CF by 30-60%. This is a substantial reduction for these products, but a small reduction in view of the total GHG emissions from the complete average diet. This illustrates the importance of calculating CF values of food and setting the results in perspective.

Keywords: carbon footprint, food, uncertainty, pollution swapping, consumer, communication, seasonal, meat guide, life cycle assessment

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Dedication

To Asta, Vera and Eskil

Everything should be made as simple as possible, but not simpler.
Albert Einstein

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 Röös, E., Sundberg, C. and Hansson, P.-A. (2010). Uncertainties in the carbon footprint of food products: a case study on table potatoes. *International Journal of LCA* 15, 478-488.

II Röös, E., Sundberg, C. and Hansson, P.-A. (2011). Uncertainties in the carbon footprint of refined wheat products: a case study on Swedish pasta. *International Journal of LCA* 16, 338-350.

III Röös, E., Sundberg, C., Tidåker, P., Strid, I. and Hansson, P.-A. (2013). Can carbon footprint serve as an indicator of the environmental impact of meat production? *Ecological Indicators* 24, 573-581.

IV Röös, E. and Tjärnemo, H. (2011). Challenges of carbon labelling of food products: a consumer research perspective. *British Food Journal* 113 (8), 982-996.

V Röös, E. and Karlsson, H. (2013). Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption. *Journal of Cleaner Production* – in press.

VI Röös, E., Ekelund, L. and Tjärnemo, H. Communicating the sustainability of meat production: challenges in the development of a Swedish meat guide. Manuscript to be submitted to *Journal of Cleaner Production.*

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The contribution of Elin Röös to the papers included in this thesis was as follows:

I Planned the paper together with the co-authors. Carried out the data collection and simulation. Wrote the paper with input from the co-authors.

II Planned the paper together with the co-authors. Carried out the data collection and simulation. Wrote the paper with input from the co-authors.

III Planned the paper together with the co-authors. Carried out the literature review and the statistical analysis. Wrote the paper with input from the co-authors.

IV Planned the paper together with the co-author. Carried out the literature review. Wrote the paper with input from the co-author.

V Planned the paper together with the co-author. Supervised the data collection and calculations. Wrote the paper with input from the co-author.

VI Planned the paper together with the co-authors. Carried out the literature review and the construction of the guide. Wrote the paper with input from the co-authors.

Abbreviations

ALCA	Attributional life cycle assessment
C	Carbon
CF	Carbon footprint
CH_4	Methane
CLCA	Consequential life cycle assessment
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
dLUC	Direct land use change
ECM	Energy corrected milk
FAO	Food and agriculture organization of the united nations
GWP	Global warming potential
iLUC	Indirect land use change
IO LCA	Input-output life cycle assessment
IPCC	Intergovernmental panel on climate change
ISO	International organization for standardization
LCA	Life cycle assessment
LCSA	Life cycle sustainability assessment
LUC	Land use change
MC	Monte Carlo

1 Introduction

1.1 Climate change and the food system

Combating climate change is one of the most pressing challenges for humanity. Emissions of greenhouse gases (GHG) arise mainly from the combustion of fossil fuels in the energy and transport sectors. However, the food sector has been identified as another major contributor to anthropogenic climate change (*Figure 1*). In Europe, food consumption is responsible for approximately 30% of total GHG emissions (EC, 2006).

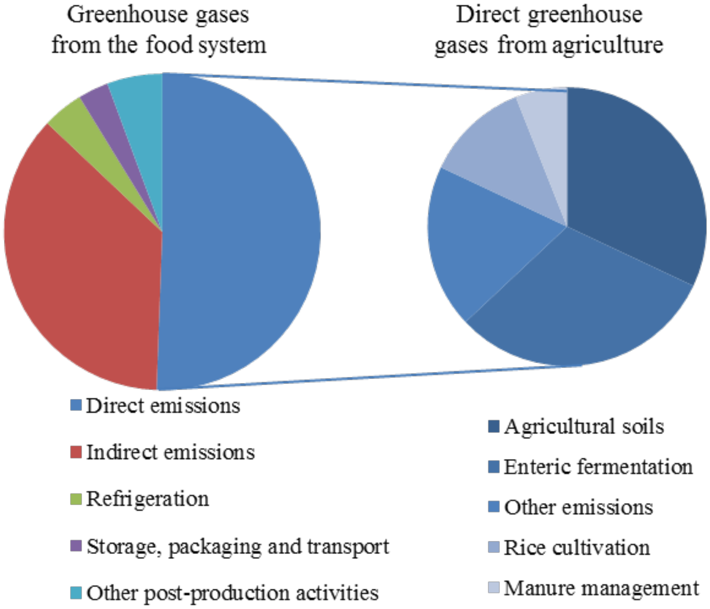

Figure 1. Greenhouse gases emissions from the food system and direct greenhouse gas emissions from agriculture (data from CCAFS, 2013). Indirect emissions are caused by deforestation when new agricultural land is taken into production.

The main processes that are directly associated with food production and which contribute to emissions of GHG are:

Pre-farm processes:

- Production and transport of inputs to the farm, most importantly feed and fertilisers, but also fuels, pesticides, growth substrates, pharmaceuticals, machinery, buildings, other capital goods *etc*.

On-farm processes:

- Soil emissions
- Emissions from enteric fermentation in animals
- Emissions from manure management
- Emissions from energy use on fields, in greenhouses, in animal houses *etc*.

Post-farm processes:

- Slaughtering
- Processing and packaging
- Storage and refrigeration
- Transport and distribution
- Retail and wholesale
- Preparation
- Digestion and waste disposal

Unlike the GHG emissions from energy consumption and transports as well as the post-farm processes in food production, direct emissions from agriculture are not dominated by carbon dioxide (CO_2) from fossil fuel combustion, but by emissions of methane (CH_4) and nitrous oxide (N_2O). These emissions arise from naturally occurring biological processes which are stimulated by anthropogenic activities such as fertilisation and keeping large numbers of ruminants. The production of food, through its demand for agricultural land, is also associated with indirect GHG emissions arising from land use change (LUC). As land is deforested and turned into cropland, large amounts of carbon bound in soils and biomass are released to the atmosphere as CO_2 (UCS, 2011; Houghton, 2012; CCAFS, 2013). However, if managed properly, agriculture also has the capability of removing CO_2 from the atmosphere through carbon sequestration in soils and biomass.

Due to the estimated global population growth to approximately 9 billion in 2050 and growing income levels, the FAO suggests that a 70% increase in food production will be necessary (FAO, 2009). This is obviously an enormous challenge at a time when climate change, biodiversity loss, land, water and energy shortage, soil erosion and chemical pollution are placing serious stress on global food production systems. It is apparent that there is a huge need to improve production systems and lower the environmental burden per kg of product produced, but also to look into other measures such as reducing food losses and changing diets.

1.2 Life cycle assessment

The improvement of food production systems and the development of more sustainable diets require solid evaluation methods. Life cycle assessment (LCA) is a well-established quantitative method for assessing the environmental impact of a product or service. Inflows of natural resources (*e.g*. raw materials, energy, land and water) to the system and outputs in the form of products, by-products, emissions and waste are quantified for all steps in the life cycle, starting at raw material extraction and continuing through to manufacturing, use and finally ending with the disposal of the product. LCA aims at being a comprehensive methodology for assessing the environmental impact of a product, hence avoiding sub-optimisation and problem shifting.

There are several types of LCA. First, a division can be made between process-based LCA and input-output LCA (IO LCA). Process-based LCA uses a 'bottom-up' approach in which the resource use and emissions from every process stage (raw material extraction, manufacturing, use, disposal) for every component (*e.g*. in the case of a bicycle; steel, rubber, electricity, machinery *etc*.) are surveyed individually. In IO LCA, economic input-output models that describe the monetary transactions between different economic sectors, such as the electricity sector, the steel sector *etc*., are extended with information on emissions to the environment. Hence, IO LCA models provide a way of studying 'transactions' of emissions between sectors and can be used to assess the environmental impact of products using a 'top-down' approach (Hendrickson *et al*., 2006). Although IO LCA has been used in LCA of food products (Weidema *et al*., 2008b), use of process-based LCA is most common.

LCA can be performed as either attributional LCA (ALCA) or consequential LCA (CLCA). Nguyen *et al*. (2010) provide a good description of the two:

> "The former [ALCA] seeks to cut the portion of the global environmental impact related to a particular product, and the later [CLCA] seeks to capture change in environmental impact as a consequence of a certain activity and thereby provides information on consequences of actions."

In ALCA average data are used, while in CLCA marginal data are used, since it is the marginal processes that will be affected by change (Weidema *et al.*, 1999). Allocation of emissions between co-products is most often based on economic or physical relationships in ALCA, while in CLCA the system is expanded to include processes that are affected by the by-products entering the market. It could be argued that all LCA studies should be performed as CLCA studies, since the results are used as a basis for decisions that will inevitably lead to change. However, some authors argue that the ALCA approach can be more appropriate when the interest lies in evaluating how the new product would perform in a future steady state rather than the dynamic impact when the product is introduced or expanded on the market (Sonesson & Berlin, 2010).

LCA is standardised by the International Organization for Standardization, ISO (ISO, 2006a, 2006b). The standard can be regarded as a framework that encapsulates the different types of LCA variants, defines basic concepts and describes how a LCA study should be structured and what it should contain, *i.e*. it gives guidance on a general level. The ISO standard for LCA stipulates that a LCA study should be structured into the following four phases:

- Goal and scope definition – depending on the subject and the intended use of the results, system boundaries and other critical modelling choices are defined in this phase, as well as a careful definition of the aim of the study.
- Inventory analysis – input and output data necessary to perform the study are collected, *e.g*. amount of resources needed and environmentally harmful emissions released to nature.
- Impact assessment – the environmental impact of the input and output flows modelled in the previous phase are assessed by sorting inventory flows into different impact categories (*e.g*. CO_2, N_2O and CH_4 cause global warming) and characterising them to one common unit (*e.g*. for global warming commonly into CO_2-equivalents, section 1.3.3), and similarly for other impact categories such as eutrophication and acidification. Impact categories can also be weighted and aggregated to get a single or a few scores describing the environmental impact and resource use.
- Interpretation – results are presented and evaluated considering completeness, sensitivity and consistency, conclusions are drawn and recommendations given.

LCA was originally limited to describing the *environmental* damage, but ways of including social issues have been suggested (Kruse, 2010). LCA can be combined with other tools to provide a more comprehensive evaluation of a product, *e.g.* life cycle costing for economic aspects.

1.3 Carbon footprint

1.3.1 History

The global focus on the issue of climate change increased after the presentation of the *Stern Review on the Economics of Climate Change* to the British government in 2006 and the release of the fourth IPCC assessment report in 2007. It was further spurred by media events such as the launch of the movie *An Inconvenient Truth* with former US senator Al Gore. This new focus on climate change was accompanied by increased interest among companies, organisations, researchers and authorities in assessing the climate impact, the carbon footprint (CF), of *e.g.* products, services, companies and sectors in the quest to reduce GHG emissions (Pandey *et al.*, 2011). Initially, private companies and NGOs drove the interest in CF and as public interest increased, the concept was also introduced in research (Weidema *et al.*, 2008a). Although the concept of CF is young, appearing initially in 2006, the climate impact of products has been calculated for decades as part of full LCA (Finkbeiner, 2009; Jensen, 2012).

1.3.2 Definition

Although there is no universally accepted definition of the concept of CF (for a summary of various definitions and units of CF see Čuček *et al.*, 2012), it has commonly been taken as *an estimate of the total amount of GHG emitted from a life cycle perspective from the product under study*, thus giving an estimate of the contribution to climate change from the product or service provided (Galli *et al.*, 2012; Jensen, 2012). If all GHG are included, the CF is exactly the same as an LCA that only takes the impact category of climate change into account. Most commonly, the most important GHG are included in the CF, although other definitions have been proposed. For example, Wright *et al.* (2011) suggested that only gases containing carbon (*e.g.* CO_2 and CH_4) should be included in the carbon footprint, while Wiedmann & Minx (2008) proposed that the CF should comprise a quantification of CO_2 emissions only. For agricultural products, such a definition of CF would not correctly reflect the impact on the climate system, as N_2O and CH_4 are major sources of GHG emissions from agriculture, and the risk of sub-optimisation is great using such a definition. Recent standardisation initiatives require the inclusion of all GHG, while admitting that including non-carbon gases in the *carbon* footprint could be confusing (Jensen, 2012).

The CF can be calculated for products or services, but also for nations or other geographical areas, academic institutions such as universities, events such as the Olympic games, individuals, households and corporations (Pandey *et al*., 2011).

1.3.3 Metrics

The CF is expressed as the global warming potential (GWP) of the GHG released during a product's life cycle. The GWP measures how much heat is trapped in the atmosphere by a certain gas relative to the amount of heat trapped by CO_2 (IPCC, 2007). The GWP value for a specific gas depends on how efficiently and in which wavelength span the gas absorbs the infra-red radiation and the life span of the gas in the atmosphere. The GWP is expressed as CO_2-equivalents (CO_2e) for different GHG, which can be added together to arrive at one measure of the climate impact from all GHG. Hence, the total GWP or CF is calculated as:

Carbon footprint or GWP_{tot} (kg CO_2e) =
= Amount of CO_2 * 1 + Amount of CH_4 * GWP_{CH4} + Amount of N_2O * GWP_{N2O}

where GWP_{CH4} is the global warming potential for CH_4 and GWP_{N2O} is the global warming potential for N_2O. The GWP of different gases depends on the time interval considered (*Table 1)*. A time interval of 100 years is usually used. Other substances such as hydrofluorocarbons and perfluorinated compounds are also strong GHG (IPCC, 2007), but their use in food production is unusual, except in some refrigerants, especially relevant for fish.

Table 1. *Global warming potential of methane (CH_4) and nitrous oxide (N_2O) for different time perspectives (IPCC, 2007)*

Gas	20 years	100 years	500 years
CH_4	72	25	7.6
N_2O	289	298	153

Indirect climate effects due to GHG emissions, such as gas-aerosol interactions (Shindell *et al*., 2009), are not included in the GWP concept. Changes to the climate system as a consequence of food production might also be caused by phenomena such as decreased evapotranspiration, aerosol formation and changes in albedo, which can have both cooling and warming effects (Höglund *et al*., 2013). Quantifying these effects is highly uncertain and has so far not been included in CF of food products.

1.3.4 Standardisation

The ISO standard for LCA (ISO, 2006a, 2006b) provides a substantial amount of flexibility to allow for a wide range of different types of studies to suit different goals. With the aim of providing more precise and consistent methodology for calculating CF, several standards or specifications on the subject have been or are being developed. The first one was PAS 2050, developed by the British Standards Institution and released in 2008. An updated version followed in 2011 (BSI, 2011) and in 2012 a version specifically targeted at calculating CF for horticultural products was released (BSI, 2012). Other CF standardisation initiatives include the GHG Protocol (WRI & WBSCD, 2011), and the on-going work in ISO to standardise the methodology for calculation of product CF (ISO 14067). An example of a standardisation initiative specifically targeted at food production is the ENVIFOOD Protocol (Food SCP, 2012). Several company- and sector-specific 'standards' have also been developed. For example, the global dairy industry, through the International Dairy Federation (IDF), has developed a common approach for calculating the CF of milk and dairy products (IDF, 2010). Another example is the guidelines developed by the beverage industry (BIER, 2010).

1.4 Carbon footprint of food

Numerous CF studies and LCA studies including the GWP from food have been performed. Roy *et al.* (2009) provide a review of LCA of food products and several studies have complied LCA results from livestock production (de Vries & de Boer, 2010; Nijdam *et al.*, 2012). *Figure 2* shows average CF values for some common food items.

The CF of different food products is highly variable, even for the same food product, depending on the production system and methodological choices in the CF assessment. However, one pattern that has emerged is that livestock products generally have a considerably larger CF than plant-based foods (EC, 2006), although high CF values for plant-based foods have been identified for some products that are produced in heated greenhouses, transported by air or produced in low-yielding systems (Stoessel *et al.*, 2012). Beef and lamb meat have exceptionally high CF, followed by cheese, due to the contribution of CH_4 from enteric fermentation in ruminants. Meat from monogastric animals, such as pigs and poultry, shows lower CF values than products from ruminants, but still higher than most foods of vegetal origin, due the large amount of feed needed in livestock production and emissions from manure handling. These numbers do not include emissions from LUC or from carbon sequestration in soils.

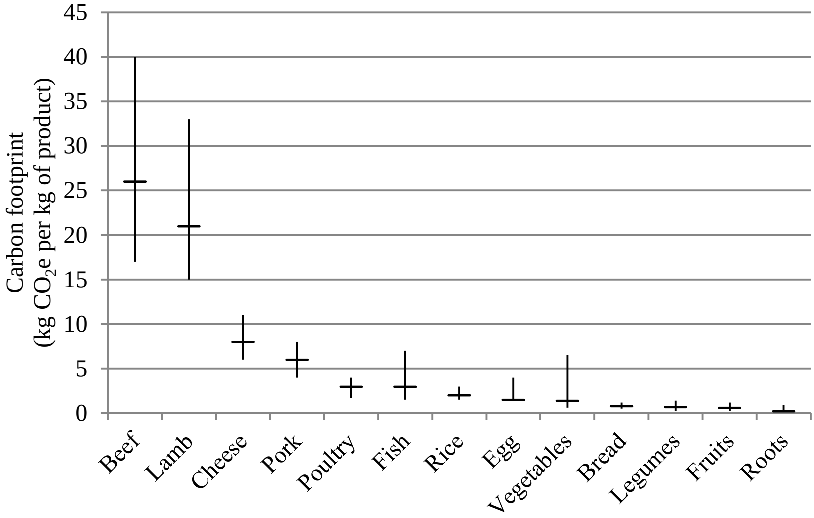

Figure 2. The carbon footprint of different types of food including emissions up to retail. Average values are estimated to be representative for foods sold on the Swedish market. Error bars show ranges of values found in the literature, and are the result of different production systems and different methodological choices. Emissions from land use change and from carbon stock changes in soils not included (from Röös, 2012).

Another important insight from studying the CF of food is that direct emissions from livestock production are dominated by pre-farm and on-farm emissions, while post-farm emissions are often considerably smaller (Cederberg *et al*., 2009a; Peters *et al*., 2010). For plant-based foods, post-farm stages can make a significant contribution to the total CF, *e.g*. emissions from transport can be a major contributor to the total CF for fruit and vegetables (Sim *et al*., 2007; Weber & Matthews, 2008).

1.5 Hopes and fears regarding carbon footprint

The obvious advantage of CF compared with full LCA is of course the reduced need for data and modelling, which drastically reduces the resources and time needed to perform an assessment. Communicating full LCA results is also challenging. If the results are presented as separate mid-point indicators, *i.e*. as GWP, eutrophication potential, land use *etc*., these need to be interpreted and weighted by the decision maker. If these impacts are translated into actual environmental damage and weighted to fewer end-scores, the subjectivity and uncertainty increase. Presenting and interpreting the single impact category of the CF is considerably easier. Hence calculating the climate impact of products has gone from a rather isolated research activity to one involving a large number of actors. Examples of the popularity of the CF concept are the multitude of carbon footprint calculators available on the Internet (Čuček *et al*., 2012), the number of CF labelling and standardisation initiatives globally (section 4.1 and 1.3.4) and an explosion of scientific papers on the subject of CF (953 papers published in 2012 found when searching for 'carbon footprint' in Scopus, compared with five in 2006).

Turning to the weaknesses, the concept of CF has been criticised for violating the basic principle of LCA, which aims at being a comprehensive method for assessing environmental impact, while the CF is limited to only one impact category (Weidema *et al.*, 2008b; Finkbeiner, 2009; Schmidt, 2009; Jungbluth *et al*., 2011). This type of criticism is not new; all types of single issue indicators have been questioned by the LCA community for their limited scope (Udo de Haes, 2006). One of the major strengths of LCA is of course its comprehensiveness, which avoids problem shifting, *e.g*. from one life cycle phase to another, from one geographical region to another or from one environmental aspect to another. It is fear of the latter, *i.e*. reducing the CF but risking aggravating other environmental aspects, that has led to concerns about calculating, communicating and acting on the CF. Furthermore, although simpler than a full LCA, calculating CF is still associated with considerable uncertainty and modelling assumptions can heavily influence the results. Hence, concerns have been raised about using apparently exact CF values for everyday decision making, when behind these numbers lies a range of data uncertainty and modelling choices (Schmidt, 2009).

The strength and weaknesses summarised here are those voiced within the research community with the introduction of CF in 2007-2009, when industries, retailers, governments and organisations expressed great hopes for CF of foods in reducing the climate impact of the food sector. The question is whether the perceived hopes and fears regarding CF are real, particularly in the specific case of food, the sector in which CF has been used most extensively for consumer communications. For example, with what precision can CF values for food be calculated? What are the major uncertainties? How should CF numbers be communicated to consumers and do consumers care, *i.e*. will presenting CF values to consumers translate into sustainable consumption? If numbers are ineffective, are there other more effective ways of communicating the CF of food to consumers? Furthermore, is there a real risk of problem shifting if producers start focusing on reduced GHG emissions over other aspects and if consumers start buying low CF food? If so, how can these goal conflicts be handled and communicated to consumers? These questions illustrate the context of this thesis and form the basis for the overall aim and research objectives, which are described in the next section.

2 Objectives and structure of the work

The overall aim of this thesis was to provide additional knowledge regarding calculating and acting on the CF of food products in order to facilitate the design of effective consumer communication strategies.

Inspired by the strengths and weaknesses voiced for food CF in the literature at the start of the work, as outlined in section 1.5, a specific objective was to study how precisely the CF of food items can be calculated using different data collection strategies and to identify parameters and processes that influence the uncertainty in the end result. This was investigated in **Papers I** and **II**, while the literature review in **Paper III** provided insights into the variability of CF values for meat. The main objective of **Paper III** was to evaluate CF as an indicator of the wider environmental impacts of meat production in order to increase knowledge of possible pollution swapping when using the single indicator CF.

Paper IV comprised a critical reflection on the usefulness of CF labelling of food products with the objective of learning more about consumer reactions to CF labelling. It emerged in **Papers I-IV** that it might be wiser to communicate with consumers using simple, easy to grasp recommendations rather than presenting numerical CF values on *e.g.* food packaging. The aim of **Paper V** was to study the reduction potential from one such simple recommendation, that of ‘eating seasonal’. Finally, the main objective of **Paper VI** was to describe the challenges in the development of a ‘meat guide’ that provided information about the CF of meat products in an attractive way, while at the same time highlighting relevant trade-offs, based on knowledge gathered in **Papers III** and **IV**.

Most of this thesis was performed within an interdisciplinary research project that involved LCA researchers and economists specialising in marketing and consumer communications. This allowed both calculation and communication aspects as regards CF of food to be included to varying degrees in all papers (*Figure 3*). However, the emphasis throughout the thesis was on calculation aspects, with a strong linkage to communication in most parts.

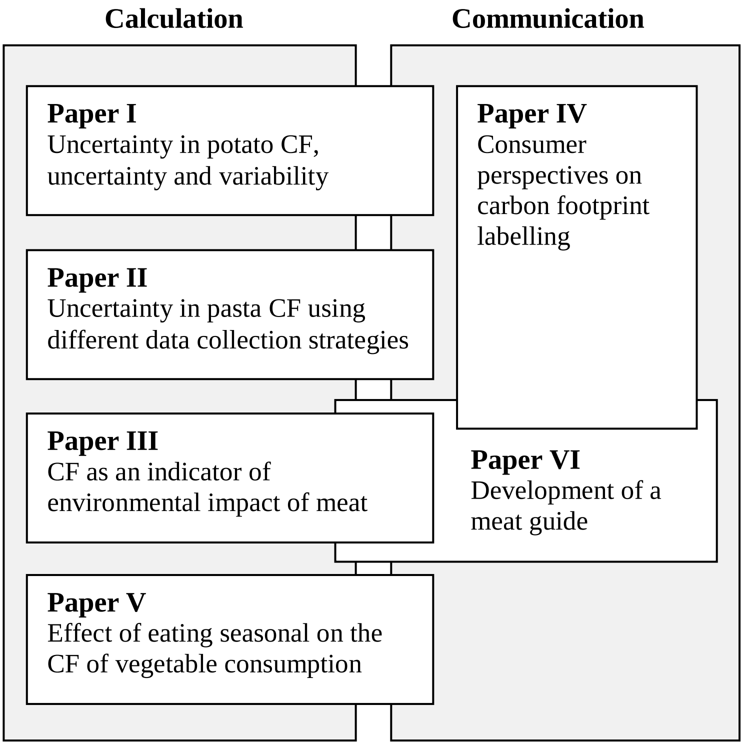

Figure 3. Papers included in this thesis and an illustration of the extent to which aspects of calculating and communicating carbon footprint are included in each. **Paper VI** builds on knowledge gathered in **Paper III** and **IV**.

The remainder of the thesis is structured as follows. Chapter 3 contains a discussion of issues related to *calculating* the CF of food, including references to the relevant papers included in the thesis. Chapter 4 discusses several aspects of *communicating* the CF of food, while Chapter 5 contains a general discussion of using CF to encourage consumers to adopt more sustainable eating habits. The thesis ends by formulating the main conclusions and outlining some implications of the results and some perspectives of the work in Chapter 6.

3 Calculating the carbon footprint of food

Many of the challenges encountered when calculating CF of food are also common when calculating CF of other products and LCA in general, but some are specific to agricultural production (*Figure 4*).

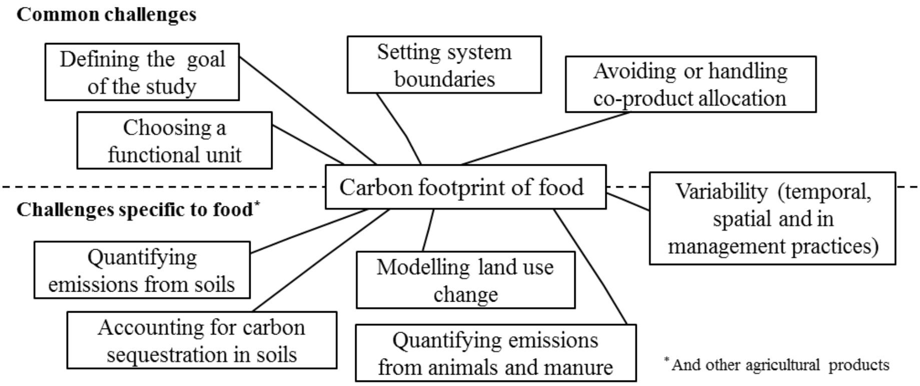

Figure 4. Challenges in calculating the carbon footprint of food. Above the dotted line are challenges that are common to carbon footprint calculations and life cycle assessments of all types of products, while challenges that are specific to food (and other agricultural products) are listed below the dotted line. Variability is relevant in all types of studies, but is especially challenging in agricultural production, which is often performed by a large number of small farms with high variability in production systems, climate and soil conditions.

Defining the goal and scope of the study is critical and a common challenge to all types of studies. This includes opting to perform either an attributional or consequential study (section 1.2), a decision which involves designing a study that will answer the relevant question. The basis for comparison, the functional unit, can also require considerable consideration when it comes to food, as further discussed in section 3.1. Another classical LCA challenge is that of co-product allocation, *i.e.* how to divide emissions and resource use from a joint production system between the different products produced, which is described briefly in section 3.2, together with the challenge of how to draw system boundaries for food.

The biological processes giving rise to GHG emissions from soils and animals in agriculture are difficult to control and measure, which makes the assessment of these emissions highly uncertain. Soil can also sequester carbon under certain conditions. These aspects are discussed in sections 3.3-3.4. GHG emissions also arise from energy use in agriculture and later steps in the food chain which is briefly described in section 3.5. Several aspects make data collection from agricultural production different to data collection from industrial production. Agricultural production is often performed by a large number of small farms which show high variability in production systems, climate and soil conditions. Section 3.6 discusses how to handle such variability and other uncertainties in CF calculations, while section 3.7 deals with seasonality, a unique feature of agricultural production. Another great complexity in food CF calculation is modelling LUC, an important contributor to food GHG emissions. Emissions of GHG from LUC are discussed in section 3.8.

3.1 Functional unit

In LCA the environmental impact is measured relative to the 'functional unit', which describes the function of the product or the service in a quantitative manner. The most commonly used functional unit for food products is simply the production of one kg of the food being studied, often also with a specification regarding system boundaries (section 3.2). Hence, the functional units in **Papers I** and **II** were '*1 kg of table potatoes available for purchase in a 2-kg 'kraft' paper bag at a Swedish supermarket*' and '*1 kg of KGI (a specific pasta variety) in paper packaging available for sale in a supermarket in Stockholm*', respectively. Since the purpose of these papers was to quantify the uncertainty in CF, rather than compare different food products, the choice of functional unit was not crucial. However, in LCA and CF studies comparing different alternatives for the same function, it is crucial that the functional unit is chosen so that the products can be compared fairly. As an example, in studies comparing milk production systems, the functional unit should account for differences in nutrient content in the milk, so metrics that include *e.g.* the fat and protein content of the milk are commonly used, *e.g.* Energy Corrected Milk (ECM) (Sjaunja *et al.*, 1990).

In **Paper V**, which studied the effects of 'eating according to season' on the CF of vegetable consumption, the functional unit was '*the yearly Swedish per* *capita consumption of tomatoes and carrots*' or, more specifically, 10.4 kg of tomatoes and 9.2 kg of carrots. This functional unit was chosen to keep the nutrient content constant for the different scenarios studied (*Table 4*, section 3.7.1). **Paper V** includes a discussion of the need for an alternative functional unit, including nutrient content, when studying scenarios containing *e.g.* more carrots and fewer tomatoes.

When comparing different livestock products and especially when comparing livestock products to alternative protein sources, it can be argued that the comparison should be done per kg of protein rather than per kg of product, since livestock products are major sources of protein in the Western diet, and since protein content varies between products, *e.g.* eggs contain 12% protein and most meats and dried legumes approximately 20%. However, it is important that the functional unit represents the *function* of the product being studied. In most developed countries average protein intake is far beyond recommendations and many consumers also over-consume food in general (Westhoek *et al*., 2011; Moomaw *et al.*, 2012). Thus it could be argued that the function of food in such countries is to supply pleasure rather than nutrients, which could motivate the use of mass as the functional unit for meat and meat substitutes after all. In addition, when consumers shop for food they shop for quantities rather than nutrients, *e.g.* a serving of sausage in a meal is often the same size as a serving of pure meat, although the protein content in the sausage might be considerably lower. That was the reason for using '*per kg of product*' as a basis for comparison in the meat guide described in section 4.4 and **Paper VI**.

Hence, the choice of functional unit is highly dependent on the context and aim of the study. To include several nutritional aspects, foods can be evaluated based on their 'nutritional density', in which their content of different nutrients such as proteins, carbohydrates, fats, vitamins and minerals is taken into account and weighted according to the recommended daily intake (Saarinen, 2012), which is relevant in *e.g.* dietary planning and in evaluating individual food products in food-scarce areas. In low-income counties, livestock also has other functions, *e.g.* providing manure for fuel, draught power and financial insurance, which need to be considered.

3.2 System boundaries and allocation

The system boundaries specify which processes are included in the product system under study. Typically, a product system for the production of food should include the processes listed in section 1.1. However, the system boundary of food CF commonly ends at the farm ('cradle-to-farm gate') or at the retail outlet ('cradle-to-retail') or at the plate ('cradle-to-plate').

Some authors strongly advocate that the full life cycle, including the use phase, be included in the CF (Schmidt, 2009; PCF Project, 2009) and this is also a requirement in most standardisation initiatives. However, the human digestion and management of human waste is seldom included, although methods to do so have been proposed (Muñoz *et al*., 2008).

Inclusion of the post-retail phases can be critical in determining the most climate friendly food alternative. This was illustrated in a study comparing potatoes and pasta based on results from **Papers I** and **II** (Röös, 2011b). When the cradle-to-retail CF values of potatoes and pasta were compared, the potatoes were clearly favourable (0.080-0.16 kg CO_2e/kg potatoes) compared with the pasta (0.41-0.50 kg CO_2e/kg dry pasta). However, when post-retail considerations were included (serving size, losses in the household and energy needed for preparation), there was only a 72% probability that serving pasta had a higher climate impact than serving potatoes. Hence, if potatoes are prepared in an energy inefficient way, *e.g*. baked in the oven, one serving of potatoes has a larger CF than one serving of cooked pasta. This illustrates one of the complexities of including the use phase in the CF of food, *i.e*. the great variability in how food can be stored and prepared.

Transport from the retail outlet to the home is also a stage that shows great variability; either it can have very little impact (if done by foot) or a large impact (if done by private car). In addition, the final transport, use and disposal of the food product are to a large extent beyond the control of the producer, as it is steered by consumer behaviour. For these reasons, Jungbluth *et al*. (2011) suggest that it makes more sense for the system boundaries to coincide with the system boundaries of what the consumer pays for. This means ending the system boundary at the retail outlet for food products bought in a supermarket, at the restaurant for a meal bought in a restaurant and so on. However, to determine the final climate impact from different food products in a supermarket, the post-retail emissions and portion sizes have to be factored in by the consumer. This is complicated and hardly feasible for ordinary supermarket consumers, but could be realistic for food professionals who have the dedicated time and resources to deal with such complicated purchase decisions (this is further discussed in Chapter 5).

One classical LCA topic that arises in most studies is how to handle the fact that many processes produce more than one product. This 'allocation problem' can be handled in several ways. A typical allocation problem in LCA on livestock products arises in the joint production of milk and meat, which has been studied extensively (Cederberg & Stadig, 2003; Flysjö *et al*., 2011a).

Examples of other allocation issues that arise in food production systems are: allocation between the food products produced in a livestock system and other outputs such as manure, wool and leather and allocation to the part of the crop used for human food and animal food. For example, in production of oilseeds, the oil is used for human consumption and the meal for animal feed. Furthermore, due to the practice of growing crops in rotation, it can be difficult to separate the processes belonging to different products in agricultural production. For example, if green manure is grown in one year, the fertiliser effect from this activity will be beneficial for several crops to follow.

Papers I and **II** used economic allocation when needed, *e.g.* allocation of emissions between the flour and wheat bran produced in the milling process were related to the price of these products. Animal manure used as crop fertiliser was assumed to come free from burden, *i.e*. all emissions for handling and storing the manure were allocated to the livestock system, which is common practice in LCA. In **Paper V**, system expansion was used to account for the electricity produced in the combined heat and power plants used to heat greenhouses in the Netherlands. It was assumed that the electricity produced replaced electricity corresponding to the Dutch electricity mix. The choice of average electricity mix heavily influenced the results; if marginal electricity had been used instead (as would have been the case in a CLCA study), the Dutch tomatoes would have had a similar CF to Swedish tomatoes produced in biofuel-heated greenhouses.

Another complexity related to the system boundaries and the calculation of CF of agricultural products is the large area of land used in agriculture. When comparing two agricultural systems, they may produce the same products, but use different amounts of land. It could be argued that alternative uses of the land 'spared' should be included in the assessment (McLaren, 2010). One such use could be to grow bioenergy crops on the surplus land, which would lower GHG emissions from society by substituting for fossil fuels. Hence, the more land-efficient production system could then be seen as having a lower climate impact when this substitution effect is included.

GHG emissions from the production, maintenance and waste handling of capital goods (buildings and machinery used in production) are commonly omitted from the system boundaries of food CF due to difficulties in data collection and allocation issues (McKinnon, 2010). The PAS 2050 specification explicitly states that emissions associated with capital goods should not be included. For many (but not all) industrial products, the contribution of capital goods to the total CF is minor due to a high utilisation rate over their life time, but for agricultural products it can be important (Frischknecht *et al*., 2007). In **Papers I** and **II**, emissions associated with capital goods accounted for approximately 6-7% of total emissions in the production of potatoes and dried wheat. In the case of tomatoes, emissions from greenhouse construction contributed 3-76% to the total tomato CF (**Paper V**). The higher values were for unheated greenhouses for which there were no emissions from heating. When emissions from capital goods are not included in the CF there is a bias towards highly industrialised production systems, which is a disadvantage for developing countries (Bolwig & Gibbon, 2009). This is further discussed in section 4.1.3.

3.3 Emissions and sequestration from/in soil

This section discusses the GHG emissions arising from the use of soils, which dominate the GHG emissions in agricultural production. The discussion here is limited to emissions which arise from cultivation of existing agricultural soils, while emissions caused by land use change are discussed in section 3.8.

3.3.1 Nitrous oxide from managed soils

Emissions of N_2O from soil are the largest source of GHG emissions in agriculture. N_2O is a potent GHG, with emissions of 1 kg N_2O giving rise to the same effect on the climate system as approximately 300 kg of CO_2 in a 100-year perspective (*Table 1*, section 1.3.3).

N_2O is formed in soils by the biological processes of nitrification and denitrification. Nitrification is the microbiological process by which ammonium reacts with oxygen to form nitrate. Denitrification involves the conversion of nitrate into nitrogen gas, in which N_2O is formed as a by-product. Factors that affect the emissions of N_2O are soil properties and climate conditions, as well as the type of crop and farming system. The risk of N_2O emissions increases with the amount of plant-available nitrogen in the soil, combined with the absence of a crop that can take up the nitrogen. When N_2O is formed in agricultural soils these emissions are called direct N_2O emissions, as they occur in the farming system itself. Indirect N_2O emissions are caused by nitrogen which is lost from the agricultural system by volatilisation (ammonia) and leakage and runoff (nitrate) (IPCC, 2006).

N_2O emissions from soil are difficult to quantify for several reasons. Measuring N_2O from large fields is expensive and challenging and N_2O emissions show considerable variation in space and time. Major emissions usually occur on a few occasions annually (Nylinder *et al.*, 2011). The most common way of estimating N_2O emissions from soil in LCA and CF calculations is to use the Tier 1 method from the IPCC (IPCC, 2006), which was also the method used in **Papers I**, **II** and **V**. This method estimates N_2O

emissions by assuming that 1% of nitrogen applied to mineral soils as mineral fertiliser, manure and crop residues is emitted as N_2O, while indirect N_2O emissions are estimated as 1% of nitrogen from volatilisation and 0.75% of leached nitrogen. The uncertainty range is large, which reflects the large variability in emissions and uncertainty in the method. There are more advanced models for assessing N_2O emissions, but these commonly require detailed soil data, which are usually not readily available (Röös & Nylinder, 2013). The way in which the uncertainty in N_2O emissions affected the results in **Papers I** and **II** is described in sections 3.6.3-3.6.5.

3.3.2 Methane from managed soils

Rice production releases CH_4, as organic matter is anaerobically decomposed in the flooded rice fields. The CH_4 emissions depend on the water management, fertilisation, soil type and temperature, among other factors (IPCC, 2006). Due to these CH_4 emissions, rice has a larger CF than *e.g.* potatoes and pasta (for potatoes and pasta see *e.g.* **Papers I** and **II** and for rice see *e.g.* Blengini & Busto, 2009; Kasmaprapruet *et al*., 2009; Nemecek *et al*., 2012).

3.3.3 Carbon dioxide to and from managed soils

Large amounts of carbon are stored in agricultural soils, which can act as either carbon sources or carbon sinks. When the soil acts as a carbon sink, this is positive from a climate perspective, as CO_2 is removed from the atmosphere and the carbon is stored in more stable forms in the soil. Much has been written regarding the possibility of slowing climate change though carbon uptake in soils and soil carbon sequestration has been recognised as one of the most important strategies for climate change mitigation (*e.g.* Freibauer *et al*., 2004; Smith *et al*., 2008).

Management practices, input of biomass, climate conditions and soil characteristics determine whether a soil loses or sequesters carbon. Tillage speeds up the oxidation of carbon compounds into CO_2, while the addition of carbon to soils in the form of roots, crop residues, animal manure and other organic material is a prerequisite for carbon storage (Lal, 2004). Soils very rich in carbon, so-called organic soils as opposed to mineral soils, lose large amounts of carbon annually as carbon is rapidly oxidised into CO_2 in these soils.

Since the stock of carbon in agricultural soils is large, small changes in soil carbon are of great importance for the overall GHG balance, but few studies to date have included carbon emissions or uptake arising from changes in soil organic matter in LCA and CF calculations of food products (see Bosco *et al*., 2013 for review). **Papers I** and **II** included emissions due to changes in soil carbon in the CF of potatoes and pasta, respectively, using the ICBM model (Andrén *et al.*, 2004). As input, this model requires the initial carbon content in the soil and the annual addition of carbon in fertilisers and crop residues. The humification factor (h) and a factor summarising the effect of temperature, water content, and tillage intensity (r_e) are used to estimate the change in the carbon pool during one year. In both **Paper I** and **Paper II**, the soil acted as a carbon sink on average, but the uncertainty was large and in the case of potatoes (**Paper I**), the soil varied from being a sink to being a carbon source. This illustrates the large variation in changes in carbon pools during cultivation, as well as the high uncertainty in modelling these changes. Bosco *et al.* (2013), who modelled changes in soil organic matter using another soil model for the CF of wine, also found that the carbon sequestration rate was highly uncertain (±70%).

Some grassland that is not ploughed and has large growth of biomass below and above ground can store large amounts of carbon (Soussana *et al.*, 2007). Hence, including carbon sequestration in the CF of food products can heavily influence the results, especially for livestock products where the animals graze large areas of grassland. For large carbon sequestration rates, the uptake of CO_2 in soils can cancel out the emissions from enteric fermentation, manure and feed production, as illustrated in *Figure 5*. Again, the potential of soils to store carbon is highly variable. One long-term trial in Sweden showed no net accumulation of soil carbon in grassland during a 65-year period (Kätterer *et al.*, 2008).

Apart from estimates of soil carbon sequestration being highly uncertain and models complex to use, there are also other methodological challenges in including soil carbon sequestration in the CF of food products. One very important aspect is that the process of storing carbon is reversible, *i.e.* if management practices change, *e.g.* if grasslands are turned into croplands, carbon stored in soils is slowly released to the atmosphere as CO_2 again. While this risk is small for some types of semi-natural grassland unsuitable for annual cropping, the carbon sequestration potential is also sensitive to heat and drought, which affect biomass growth and ecosystem respiration (Soussana *et al.*, 2007). In addition, although there are some indications that sequestration can take place even in old grassland (Soussana *et al.*, 2007), conventional soil science builds on an assumption of soil saturation. That means that in the absence of changes in management and environmental factors, soils will reach equilibrium in terms of carbon. Thus, although carbon sequestration can continue for many (hundreds of) years, the potential to store carbon in the soil will diminish with time (Powlson *et al.*, 2011; Smith, 2012). For these reasons, in the meat guide developed within this project (**Paper VI** and section 4.4), carbon sequestration was not included.

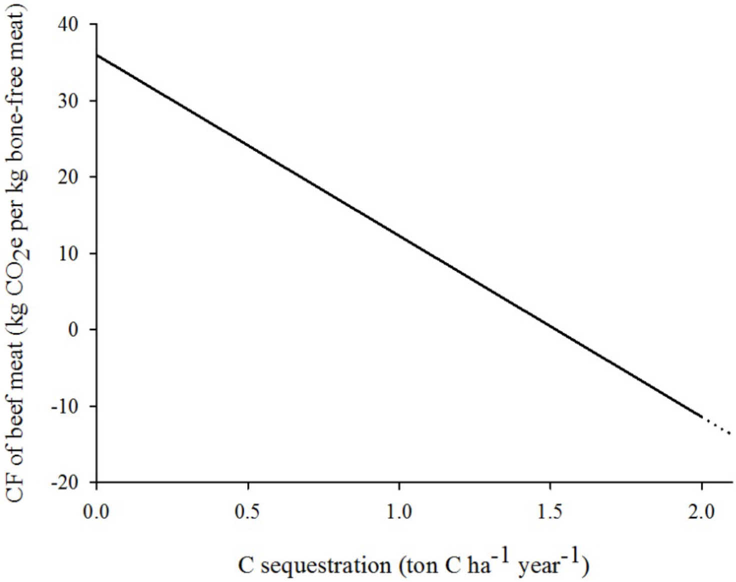

Figure 5. Carbon footprint (CF) of beef meat for different levels of assumed carbon (C) sequestration in soils. Carbon footprint without any sequestration is assumed to be 36 kg CO_2e per kg bone-free meat, corresponding to extensive beef production in Sweden with grazing during summer and mainly roughage feed during winter and a slaughter age of 22 months (based on data from Cederberg *et al*., 2009b).

For food products grown in perennial systems, *e.g*. nuts, fruits and olives, it is relevant to consider temporary storage of carbon in biomass such as trees. Brandão *et al*. (2013) provide a good summary of this issue.

3.4 Emissions from animals and manure

3.4.1 Enteric fermentation in ruminants

Emissions of CH_4 from enteric fermentation in ruminants are a major source of GHG emissions from agriculture (*Figure 1*, section 1.1). Monogastric animals such as pigs also emit $CH_{4,}$ but in much lower amounts than ruminants. Ruminants have the ability to digest cellulose and thereby utilise roughage feed such as grass for growth and milk production through a highly specialised digestive system. In the process in which microorganisms in the rumen digest fibre-rich feed material, CH_4 is formed as a by-product. The CH_4 is released to the atmosphere mainly with the exhaled breath (IPCC, 2006).

Several different models for estimating the CH_4 emissions from cattle have been developed. Empirical models based on observed CH_4 production use feed characteristics such as total dry matter intake, different types of energy measurements, fibre and fat content *etc*. and/or animal production data such as body weight, weight gain or milk production to predict emissions (Ellis *et al*., 2007, 2009, 2010). There are also mechanistic models in which the functioning of the rumen is modelled mathematically. So far empirical models have been most commonly used in LCA and CF calculations, since the input data needed for these models are more commonly available and mechanistic models are often too complex to be used on farm level (Gibbons *et al*., 2006).

Several studies have evaluated models for estimating enteric fermentation from ruminants by comparing measured values with values predicted by the model (Wilkerson & Casper, 1995; Mills *et al*., 2003; Kebreab *et al*., 2006; Ellis *et al*., 2007, 2010). Statistical models usually fail to give reliable predictions outside the range of intake used in their development. Most model development to date has been based on measurements of emissions from dairy cattle, so estimating CH_4 emissions from other types of cattle, *e.g.* heifers, bulls and suckler cows, and from other ruminants is even more uncertain than estimating emissions from dairy cows. Ellis *et al*. (2010) highlight the risk of designing sub-optimal mitigation options if the model used to predict the CH_4 emissions does not reflect the underlying cause-effect chain.

Furthermore, when it comes to different feeding strategies for reduced CH_4 emissions, emissions from production of the feed need to be included as well. This is because some feedstuffs can contribute to lower CH_4 emissions from enteric fermentation, but cause higher GHG emissions from production, especially if these feed products are associated with land use change effects (section 3.8). Carbon uptake and sequestration (section 3.3.3), could also potentially balance out increased CH_4 emissions from enteric fermentation for some feedstuffs. This highlights the necessity to use life cycle-based assessment methods.

3.4.2 Manure management

N_2O is produced in manure in storage or on pasture by the same processes as N_2O formation in soil. Solid manure systems promote N_2O formation, since they provide an opportunity for both nitrification and denitrification (section 3.3.1). Emissions of N_2O can be especially large in deep litter systems due to the good oxygen supply. Ammonia emissions can be substantial in manure management, giving rise to indirect emissions of N_2O.

In anoxic environments such as slurry systems, there is a significant risk of CH_4 release. Some important factors that affect the amount of CH_4 produced during the storage period are temperature and the carbon content and pH of the manure (IPCC, 2006). At low temperature the microbial activity is reduced, giving rise to less CH_4 formation. By feeding the manure to a biogas reactor, the CH_4 from the manure can be captured and used as bioenergy. Concentrated manure on pasture or feedlots and stored solid manure that is not well aired also give rise to CH_4 emissions.

Most LCA studies use IPCC Tier 2 methodology for calculating the GHG emissions from manure management (IPCC, 2006), although more complex and targeted methods for estimating emissions from manure storage are available (*e.g.* Sommer *et al.*, 2004). However, these models require sophisticated input data that are not readily available on farms. The IPCC emission factors for manure management are highly uncertain, *e.g.* that for direct N_2O emissions from manure management is associated with an uncertainty of -50 to +100%. This is due to the complex and highly variable processes driving N_2O formation (section 3.3.1), as well as the varying characteristics of manure.

3.5 Emissions from energy use

Emissions of GHG from energy consumption in agriculture arise mainly from: combustion of fuels used in field machinery, the use of fossil energy sources for the production of mineral fertilisers, feed, machinery and buildings, electricity and fossil fuel use for crop drying, lighting, ventilation and *e.g.* milking equipment in dairy units, combustion of fuels for heating animal houses and combustion of fossil fuels in vehicles used for transporting *e.g.* fertilisers, feed and animals. For the entire food sector, added to these are the GHG emissions caused by fossil energy use in post-farm stages, such as transport, storage and refrigeration of food (section 1.1).

Calculating GHG emissions from the combustion of fossil fuels is straightforward, since the emissions are governed by the chemical reaction of hydrocarbon compounds in the fossil fuel being converted to CO_2 and water. Emissions from the extraction of oil and production and transport of the fuel need to added to the emissions from combustion. The uncertainty in emissions from these process steps is small compared with the uncertainties from other processes in agriculture (*Figure 6*), at least as long as conventional fossil sources are considered and not oil shale, tar sands and other unconventional sources (Eriksson & Ahlgren, 2013). Hence, the major uncertainty in assessing GHG emissions from fossil fuel use in agriculture lies in correctly assessing the actual amount of fuel used.

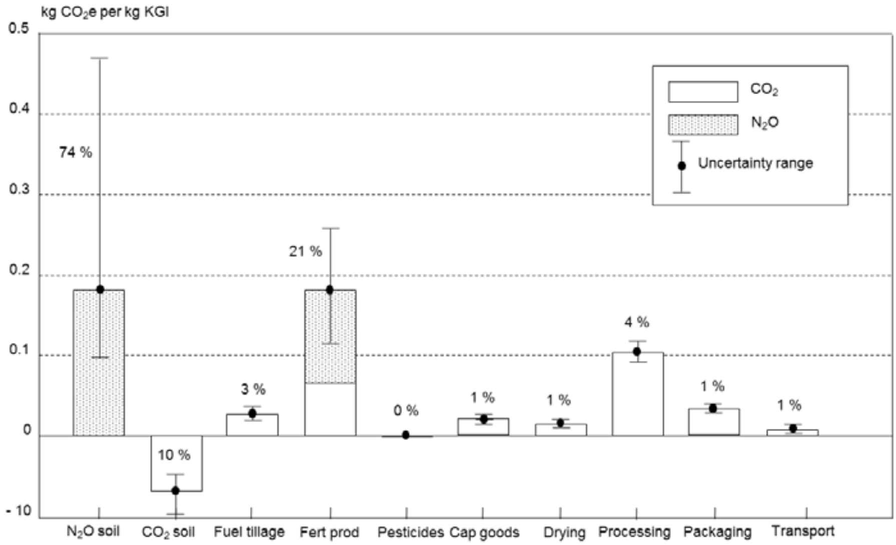

Figure 6. Contributing processes to the carbon footprint of Swedish wheat for pasta production (KGI). Error bars show uncertainty as the range between the 2.5 and 97.5 percentiles. Numbers are the relative contribution to uncertainty from an individual process as the range divided by the total mean carbon footprint (from **Paper II**).

Estimating GHG emissions from electricity consumption opens the way for several modelling choices. In ALCA the emissions from the average electricity mix are used and the challenge lies in determining the relevant mix to use, *e.g.* the national mix or whether electricity is traded on a market smaller or greater than the national borders, in which case this mix might be more relevant. In CLCA, the marginal electricity supply is used when modelling emissions from electricity, as this is the supply that will be affected when the demand for electricity increases. Determining the future marginal electricity source is far from simple (Finnveden, 2008; Lund *et al.*, 2010). For products which demand large amounts of electricity during production or use, the choice of modelling approach for electricity can have a major influence on the results as was the case in **Paper V** (section 3.2).

Manufacturing of mineral fertilisers is energy-demanding and also gives rise to emissions of N_2O. Depending on the N_2O cleaning technique used in production, total emissions of GHG from the production of mineral nitrogen fertiliser can vary greatly (*Figure 6*). If the origin of the fertiliser is known, the uncertainty in the GHG emissions from production is ±30% for a 95% confidence interval (**Paper II**), which is small compared with *e.g.* the uncertainty in soil emissions or that due to modelling choices.

3.6 Uncertainty and variation

3.6.1 Sources of uncertainty in the carbon footprint of food

When calculating the CF of food, several different types of uncertainties are introduced at different levels (*Figure 7*). The emissions of CO_2, N_2O and CH_4 coming from the complex and highly variable biological processes associated with agriculture are estimated using different more or less uncertain models, which usually only include parts of the cause-effect chain, as discussed in sections 3.3 and 3.4, introducing *model uncertainty*. The data that are fed into models, *e.g*. yield levels, energy use and types and amounts of fertilisers and feed, are also characterised by a high degree of uncertainty, but more importantly, variability, giving rise to *data uncertainty*. The uncertain model results are aggregated in the LCA model, which in itself is an uncertain and limited representation of reality built on several choices regarding functional unit, system boundaries, allocation principles *etc*., introducing *scenario uncertainty*.

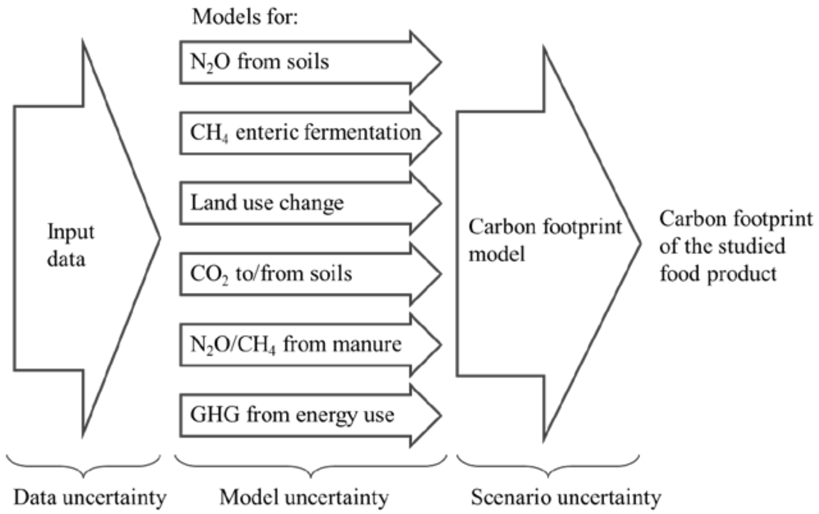

Figure 7. Many different types of uncertainty contribute to the total uncertainty in the carbon footprint of food.

In addition to the variability at farm level, the later stages of food production are highly complex, with many food products being composed of a large number of raw materials, some originating from different places around the globe depending on world market prices. This adds to the complexity of tracing GHG emissions and calculating the CF of the final product (McKinnon, 2010).

3.6.2 Handling uncertainty and variation

Uncertainty in LCA can be reduced by following standards (section 1.3.4) to ensure consistency in calculation methods, although there is a risk of the results being biased by the selection of methods and data collection strategies specified in the standard. Current CF standards provide considerable scope for interpretation, which limits their usefulness in reducing uncertainty (Jensen, 2012; Soode *et al.*, 2013). Uncertainty in input data can be reduced by *e.g.* improved data collection and additional measurements, using data from well-regarded databases and validating data. Uncertainty due to choices can be reduced using critical review and model uncertainties can be reduced by using a higher resolution model with higher precision (Björklund, 2002; Heijungs & Huijbregts, 2004).

Uncertainties can never be reduced to zero, however. Furthermore, variability is an inherent property of a system and, unlike uncertainty, it cannot be reduced by more accurate modelling of the system or collection of data. Therefore, after measures have been taken to reduce uncertainty, it is important that the remaining uncertainty is illustrated and presented as part of the results. The ISO LCA standard (ISO, 2006a, 2006b) includes a requirement on the inclusion of uncertainty and sensitivity assessment when performing LCA studies:

> "An analysis of results for sensitivity and uncertainty shall be conducted for studies intended to be used in comparative assertions intended to be disclosed to the public."

Where uncertainty is defined in the ISO LCA standard as:

> "**Uncertainty analysis** is a systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability"

and sensitivity analysis as:

> "**Sensitivity analyses** are systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study."

It should be noted that uncertainty and sensitivity analyses are used not only when presenting and interpreting LCA results but, since LCA is an iterative process, also for improving the study. For example, if uncertainty is too large in the final results, it might be possible to improve the precision with better data. If sensitivity analysis shows that some scenario choices are crucial to the results, it might be possible to improve the reliability of the results through a more refined analysis (Curran, 2013).

3.6.3 Uncertainty analysis

To establish how uncertainty and variability in input data are propagated though the CF model and affect the uncertainty in the final result, probabilistic or stochastic simulation can be used, although other ways of performing uncertainty analysis, using *e.g.* classical or Bayesian statistics or fuzzy logic, have been used to a limited extent in LCA (Björklund, 2002). Monte Carlo (MC) simulation (Rubinstein & Kroese, 2007) is the most commonly used stochastic simulation method in LCA. In MC simulation, parameters are described by a probability distribution, rather than a single deterministic value, and the calculation of the CF is repeated a large number of times, for each of which a random parameter value from the probability distribution describing the input data is used. The results of a MC simulation consist of a number of possible outcomes of the calculation, hence giving a representation of the probability of different results depending on the uncertainty and variation in the input data (*Figure 8*).

In **Papers I** and **II**, the CF of potatoes and wheat (and finally pasta) was estimated using MC simulation. Input parameters such as yield, amount of fertilisers and fuels used, soil characteristics, transport distances *etc*. were carefully investigated in order to be described as probability distributions. In **Papers I** and **II**, the variations and uncertainties were assessed separately. The distributions for variation outlined the variability between years and fields for example, while the uncertainty distributions described the precision that can realistically be assumed when collecting the data for the potato and pasta production chains (in order to estimate the precision in CF if a scheme were to be introduced today). By describing variability and uncertainty separately, it was possible in **Paper I** to study how the temporal and spatial resolution in data collection affected the final CF uncertainty. In **Paper II** this division of uncertainty and variability was used to estimate how precision in the final CF was affected by more or less careful data collection at farm level; either all farm parameters were collected or only the most influential parameters (yield, amount and type of nitrogen fertilisers and municipality in order to determine the average soil clay and humus content).

Although MC simulation is technically easy to perform, establishing relevant uncertainty representations for the input data in the form of probability distributions is often difficult and time-consuming. Data are seldom available in the abundance and form needed for classical statistical analysis and expert judgment is often needed to establish probability distributions and parameters. It is also important to cater for correlations in order to avoid overestimating uncertainty. It must be stressed that MC simulation only provides an estimate of the uncertainty arising due to the uncertainty and variability in input data and model parameters. It can give a false sense of certainty, as it is not uncommon for model uncertainties, *e.g*. the method chosen to calculate N_2O from soil, CH_4 from enteric fermentation and LUC or the allocation method used, to be much larger and to overshadow the uncertainties due to input data uncertainty and variations (Röös & Nylinder, 2013).

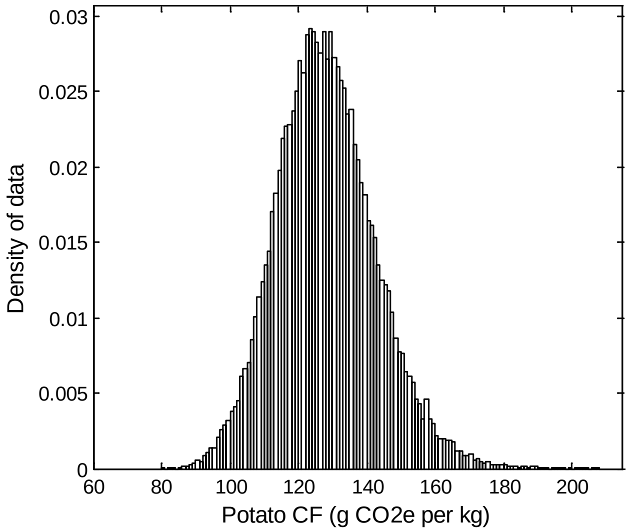

Figure 8. Histogram showing the outcome from the Monte Carlo simulation of the carbon footprint (CF) of Swedish potatoes in **Paper I** (variations and uncertainties in all input data included).

Figure 8 shows the results from the MC simulation of potato CF in **Paper I**. As can be seen from the diagram, possible outcomes of the potato CF varied from 0.080 to over 0.20 kg CO_2e per kg potatoes. However, the most probable outcome (illustrated by the height of the bars in *Figure 8*) lay between 0.10-0.16 kg CO_2e (95% of the results). This illustrates the uncertainty in CF for this potato variety (King Edward) in this region (Östergötland, Sweden) and hence the uncertainty for potatoes in general is much larger. It is reasonable to suspect, based on the yield being such an influential parameter (section 3.6.4), that the CF could easily double for a variety with a considerably lower yield.

The results from **Paper II** are summarised in *Table 2*. When data were collected from only one farm during one year (variability of farm level input data between farms and years set to zero), the range of possible CF values was still 0.22-0.56 kg CO_2e per kg wheat due to measuring uncertainty and uncertainty in model parameters (most importantly in N_2O emissions factors). This shows the best precision possible with currently available CF calculation methods and realistic farm level data collection methods from one farm. When data were assumed to be collected from several farms during several years, the wheat CF varied from 0.12 to 0.91 kg CO_2e per kg wheat due to variations in yield, soil parameters, amount of fertilisers and fuels used *etc*. However, since wheat from several farms is mixed in the production of wheat-based products, the high and low CF values were cancelled out, resulting in a considerably lower uncertainty in the wheat mix CF of only ±10-20%. Collecting all farm level parameters (advanced traceability) instead of only the most influential parameters (basic traceability) only increased the precision slightly (*Table 2*).

Table 2. *Carbon footprint ranges of Swedish wheat from Skåne (**Paper II**), calculated using different ways of collecting input data. In 'advanced traceability', data on all farm level parameters are assumed to be collected from each farm, while in 'basic traceability' data on only the most influential parameters are collected from the farms (yield, the amounts of nitrogen fertilisers and the municipality in which the farm is located for determining the typical soil characteristics). 'Farms' are values for individual farms, while 'Mix' are values for the wheat mixture used for making refined wheat products such as pasta*

Scenario		**Boundaries**		**Range**	
		Farms	Mix	Farms	Mix
1:a	One farm, advanced traceability	0.22-0.56	-	0.34	-
1:b	One farm, basic traceability	0.22-0.57	-	0.35	-
2:a	Several farms, advanced traceability				
	2001 (51 farms)	0.19-0.79	0.32-0.41	0.60	0.09
	2003 (90 farms)	0.12-0.75	0.27-0.32	0.63	0.05
	2005 (19 farms)	0.18-0.58	0.28-0.39	0.40	0.11
	2007 (159 farms)	0.12-0.59	0.30-0.35	0.47	0.05
2:b	Several farms, basic traceability				
	2001 (51 farms)	0.18-0.91	0.32-0.41	0.73	0.09
	2003 (90 farms)	0.12-0.81	0.26-0.32	0.69	0.06
	2005 (19 farms)	0.17-0.59	0.26-0.39	0.42	0.13
	2007 (159 farms)	0.13-0.65	0.30-0.36	0.52	0.06

The magnitude of the uncertainty ranges found in **Papers I** and **II** showed good agreement with those published later in other literature. For example, Flysjö *et al*. (2011b) used MC simulation to study how uncertainties in CH_4 from enteric fermentation and N_2O from soil affected milk CF and found an uncertainty range of 0.60-1.52 kg CO_2e/kg ECM for milk from New Zealand and 0.83-1.56 kg CO_2e/kg ECM for Swedish milk. Ingwersen (2012) found the CF of pineapples to be 0.06±0.02 kg CO_2e/per serving when investigated using

MC simulation. Nemecek *et al.* (2012) used an extrapolation method to calculate the CF of a large number of crops from different countries and found the coefficient of variance in the CF to be 8-41% due to variability in production parameters.

Stochastic simulation can also be used to account for uncertainty in model parameters. For example, the IPCC uncertainty ranges for emission factors for N_2O (IPCC, 2006) can be used to establish a probability distribution that can be fed into a MC simulation model, as done in **Papers I** and **II.**

3.6.4 Sensitivity analysis

Sensitivity analysis is valuable to identify the input data, model and scenario choices that are most influential for the final CF. By using different models, functional units, system boundaries, allocation methods *etc*. to calculate the results, the robustness of the calculated CF can be evaluated.

To test the sensitivity of the results to input data uncertainty, one input parameter value can be changed by a certain predefined percentage while all other parameters are kept constant. The change in the end result shows how sensitive the results are to uncertainties or variability in this specific parameter. By using actual min and max values, or *e.g.* a 95% confidence interval, for input parameters instead of an arbitrarily chosen percentage value, a better picture of the sensibility of the model is provided (called uncertainty importance analysis).

Table 3 presents the results from a simple ±20% sensitivity analysis and an uncertainty importance analysis from **Paper I**. The simple sensitivity analysis showed that the most sensitive parameters were potato yield, quality (percentage sold for human consumption) and the amount of nitrogen fertiliser used. The uncertainty importance analysis revealed that the soil humus content, the fuel spent during tillage operations, the amount of electricity spent during the packaging process, the distribution distance, and two of the emission factors for N_2O emissions from soil were also important for the end result. This clearly shows how a sensitivity analysis using fixed values for change can fail to recognise the sensitivity in the parameters with large variability, especially if these are not normally or uniformly distributed. The uncertainty importance analysis performed in **Paper II** on pasta identified the wheat yield, the amount of nitrogen fertiliser applied and the emission factors for N_2O as the most influential parameters.

Yield proved to be one of the most influential parameter in **Papers I** and **II**. This is common to all agricultural products in general, since the accumulated emissions from a cultivated area are divided across the yield from that area. Hence, maximising yields will reduce the CF, unless nitrogen fertiliser use is increased to such an extent that the emissions from the production and use of fertilisers cancel the benefits of increased yields. Hence, the amount of nitrogen fertilisers used are also important to most food CF results as it influences N_2O emissions from soil using most commonly used calculation methods (section 3.3.1) and causes GHG emissions from its production (section 3.5). Food CF is also highly sensitive to the handling of GHG emissions from LUC (section 3.8) and model choices. For a thorough review of different methods and examples of how method choice can influence results, see Röös & Nylinder (2013).

Table 3. *Change in the carbon footprint when performing sensitivity analysis and uncertainty importance analysis of individual parameters in the carbon footprint of Swedish King Edward potatoes from Östergötland (**Paper I**)*

	Sensitivity analysis		**Uncertainty importance analysis**	
	+ 20 %	**- 20 %**	**+ 2 std/ Max**	**-2 std/ Min**
Humus content	+ 1%	- 1%	+ 12%	- 4%
Yield	- 11%	+ 18%	-10%	+ 15%
Quality	- 10%	+ 16%	- 3 %	+ 3%
Fuel tillage operations	+ 2%	- 2%	+ 7%	- 3%
Amount of nitrogen fertiliser	+ 6%	- 6%	+7%	- 6%
Used energy for packaging	+ 1%	- 1%	+ 7%	- 3%
Distribution distance	+ 2%	- 2%	+ 2%	- 9%
Emissions factor N_2O background	+ 1%	- 1%	+ 10%	- 4%
Emissions factor N_2O crop residues	+ 1%	- 1%	+ 11%	- 4%

3.6.5 The importance of uncertainty assessment

Uncertainty and sensitivity analysis is necessary to establish the precision and sensitivity in the results, so that they can be presented in a way that illustrates their uncertainty. Due to the large uncertainties and variations in the calculations of food CF, it is often inaccurate for the mean value of food CF to be given to more than one or two significant figures, although this is commonly done, giving a false sense of accuracy (Schmidt, 2009; PCF Project, 2009; McKinnon, 2010; Tan *et al.*, 2012). This was clearly illustrated in **Papers I** and **II**, in which production was limited to a restricted area and crop variety, and it was still not possible to establish the CF with a precision that could justify more than two significant figures. Hence, when presenting CF values for typical potatoes and pasta in Sweden (as well as other food items), it is only justifiable to use one or two significant figures, as was done in a summary of food CF values compiled to help different actors evaluate the climate impact of food purchases (Röös, 2012; section 5.4).

When food products or production systems are being compared, it is crucial to include uncertainty assessment in order to establish whether any solid conclusions about the difference between products or systems can be established. Two overlapping CF uncertainty intervals from two different products do not necessarily mean that it is impossible to separate the products, as this depends on the correlations. If the uncertainty in CF depends on the same underlying uncertainties for different systems, *e.g.* the uncertainty in the emissions factor for the production of fertiliser, assuming that the two systems use the same type of fertiliser, this uncertainty should not be included in the uncertainty assessment. That since, the system using the least amount of fertiliser will cause less emissions from fertiliser production, however uncertain these emissions are. To account for such situations in MC simulations, the results from an iteration in the simulation are compared pair-wise for the two systems; the results for that iteration calculated using the same random emissions factor for the different systems. If the pair-wise differences between the two systems are saved for each iteration, this gives an estimate of when one system is preferable over the other. Such a comparison was done in **Paper II**, comparing 'low-emitting farms' (20% of all farms having the lowest deterministic wheat CF) with all farms forming a reference group. The result is shown in *Figure 9*. The wheat mix CF from all farms was found to be higher in 81% of cases (positive values in *Figure 9*) than the wheat mix CF from 'low-emitting' farms, showing that with rather high confidence it would be possible to separate wheat mixes from farms causing lower emissions from wheat mixes from all farms, despite large uncertainties in individual wheat CF values (*Table 2*, section 3.6.3).

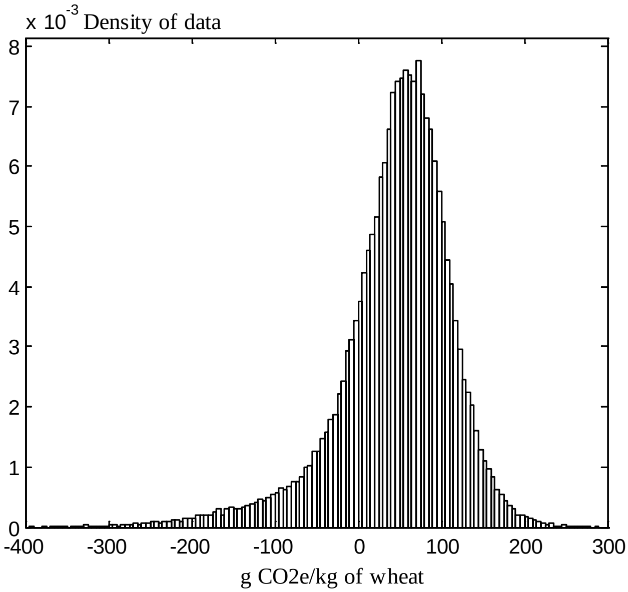

Figure 9. Histogram of the difference in carbon footprint between wheat mixes from all farms and 'low-emitting farms' in 2005 (**Paper II**).

3.7 Seasonality

3.7.1 Defining seasonality

Another aspect that differentiates food production from most industrial production is that of seasonality, *i.e.* production of foods is limited by climate conditions, including lack of heat and light during winter, which prevents plant photosynthesis and *e.g.* egg laying in poultry. Another type of seasonality is the availability of wild resources (*e.g.* fish, berries and game), which varies throughout the year. Seasonality is less pronounced today than it was in the past, as modern production techniques, *e.g.* heated greenhouses and artificial lighting, enable production of vegetables in cold climates all year around. It is questionable whether products can be regarded as seasonal when they are produced using large amounts of external energy to maintain an artificial climate. A clear definition of seasonality of food is currently lacking, but in order to research the area of seasonality and how the CF of food is affected, a definition of the concept is essential. Brooks *et al.* (2011), who studied the concept of seasonality in the UK, suggest the following two definitions:

> "Food that is produced and consumed in the same climatic zone, *e.g.* UK, without high energy use for climate modification such as heated glasshouses or high energy use cold storage"

which includes both the concept of locality and low energy input, or:

> "Food that is outdoor grown or produced during the natural growing/production period for the country or region where it is produced. It need not necessarily be consumed locally to where it is grown."

which is limited to the notion of outdoor (low energy) production.

In **Paper V**, in which the potential to reduce GHG emissions from seasonal consumption of tomatoes and carrots in Sweden was studied, four different definitions of seasonality based on descriptions of seasonal eating found on websites and in other documents from authorities and organisations promoting the consumption of seasonal foods in Sweden were used (*Table 4*). Two of these definitions included only a concept of locality, limiting production to either Sweden or Europe, while two definitions included aspects of locality, but also banned the use of external energy inputs.

Table 4. *Different ways of defining seasonal consumption found in Swedish grey literature and used in* ***Paper V***

Definition	Description	Transport	Accepts produce from heated greenhouses
A	Swedish season. Consumes only Swedish produce. Heated greenhouses allowed. Main argument: decreases transportation.	Short	Yes
B	Swedish season with no energy use for heating. Consumes only Swedish produce that has been cultivated without heated greenhouses. Main arguments: decreases transportation and energy inputs.	Short	No
C	European season. Consumes European produce with the shortest transport distance (therefore prioritises Swedish produce when this is available). Heated greenhouses allowed. Main argument: decreases transportation.	Medium	Yes
D	European season with no energy use for heating. Consumes European produce (but prioritises Swedish produce when this is available) that has been produced without heated greenhouses. Main argument: decreases energy use for greenhouses.	Long	No

All definitions used in the study in **Paper V**, as well as the first definition suggested by Brooks *et al.* (2011), include a requirement on proximity of production. However, transport mode is just as critical as transport distance for the release of GHG from transportation (*Table 5*). Going forward, to avoid confusion with aspects of reduced transport, **Paper V** recommends a more stringent definition of seasonality in line with the second definition suggested by Brooks *et al.* (2011), since growing something in season is about using natural conditions and avoiding the need for additional inputs of energy, irrigation, fertilisers and/or pesticides. However, defining what is 'natural' in modern agriculture is highly challenging, since all agriculture regardless of season is heavily dependent on several inputs.

Table 5. *Emissions of greenhouse gases (GHG) from transport*

Transport mode	Transport distance (km)	Emissions of GHG (kg CO_2e per kg product transported)	Source
Aircraft South Africa to Germany	9125	6.6	Gössling *et al.*, 2011
Ship Brazil to Germany	9732	0.15	Gössling *et al.*, 2011
Truck Spain to Germany	2333	0.37	Gössling *et al.*, 2011
Train Spain to Germany	2441	0.04	Gössling *et al.*, 2011
Ship/truck Dom. Republic to Denmark	8322	0.19	Trydeman-Knudsen, 2011
Ship/truck China to Denmark	21278	0.37	Trydeman-Knudsen, 2011
Ship/truck Costa Rica to Norway	Not avail.	2[1]	Svanes & Aronsson, 2013
Pick-up truck for local transport	100	0.20	NTM, 2013

[1]Considerably higher than other values due to small ship size and the assumption that they return empty.

3.7.2 Allocation of inputs throughout the season

Do vegetables grown in heated greenhouses, which ripen during the summer when less energy is needed in the greenhouse, have a lower CF than vegetables harvested in early spring or late autumn when energy consumption is higher? This depends on how the energy needed throughout the year in the greenhouse is allocated to the vegetables produced. If the production of vegetables in the summer is independent of the energy use during the rest of the year, *i.e.* if it would be possible to produce vegetables during the summer only, it makes sense to allocate just the energy needed during the summer to the vegetables harvested in the summer, which would result in a lower CF for these products. However, in modern, highly advanced hydroponic greenhouses heating is needed outside the growing season in cold climates to prevent sensitive equipment from freezing and potentially to melt snow falling on the roof. Heating is also needed to grow plants and the unripe fruit before harvesting starts. This baseline heating needs to be allocated to all vegetables grown during that season. Hence, in **Paper V**, which allocated the yearly energy use evenly to all tomatoes produced during a year, the CF of all tomatoes produced during a year was the same, regardless of when they were harvested. However, for the carrots in **Paper V**, emissions from the energy used during cold storage were allocated to the carrots depending on the storage time, since climate control can be turned off when the store has been emptied. Hence, carrots consumed soon after harvest had a lower CF than those consumed after a period of storage. Viewed in this way, carrots can be seen as having a more distinct season than tomatoes as modern industrial production techniques challenge the concept of seasonality.

3.8 Land use change

3.8.1 Description of land use change and calculation methods

Deforestation and other land use changes (LUC) are responsible for approximately 10% of global total CO_2 emissions (Global Carbon Project, 2013). Demand for agricultural land has been identified as the major driver of deforestation, so it is reasonable to attribute GHG emissions from deforestation to the food products driving LUC (UCS, 2011; Houghton, 2012). LUC can be divided into direct land use change, dLUC, and indirect land use change, iLUC. If land is converted and a crop is then grown on that actual site, this conversion is the dLUC caused by that crop. iLUC are changes caused by the increase in production of crops that push other crops out into non-crop land, causing deforestation.

Several methods for including GHG emissions from LUC in food CF, especially meat, have been proposed in recent years (for a comprehensive review of different methods see Röös & Nylinder, 2013). LUC can be calculated as dLUC only, or by using methods that include both dLUC and iLUC. For the latter, two fundamentally different approaches have been used. One type of method is based on the viewpoint that the expanding crops or production systems should bear the burden of emissions from LUC (Leip *et al.*, 2010; Gerber *et al.*, 2010; Ponsioen & Blonk, 2012). Using such methods results in high emissions from LUC being attributed to crops that are expanding in area, typically soy, while other crops go free from the burden. Another type of method is based on the assumption that demand for agricultural land in general contributes to commodity and land prices and therefore to LUC (Audsley *et al.*, 2009; Schmidt *et al.*, 2012). Such methods attribute emissions from LUC to all crops globally, regardless of where they are grown. Audsley *et al.* (2009) use a simple top-down approach in which all global emissions from LUC (according to IPCC, 2006) that can be attributed to the expansion of commercial agriculture are evenly divided over the total area of land used for commercial agriculture, which gives an LUC factor of 1.43 ton CO_2e per ha. Schmidt *et al*. (2012) propose a more elaborate model which distributes emissions across different types of land according to the ability of the land to produce biomass.

Emissions from LUC can also be estimated using economic equilibrium models that employ actual economic data to estimate how an economy reacts to changes in policy. Such models have been used extensively to predict possible LUC due to different biofuel policies. The results from these economic models are highly variable, which can be expected to some extent as the models describe very complex and varying future scenarios which are inherently uncertain. Furthermore, there is variation due to different modelling approaches, *e.g*. modelling the entire world economy or only the agricultural sector, geographical resolution in crop trading and whether land expansion is allowed on pasture and/or forest land. In addition, parameters such as yield levels and amount of by-products differ between studies (Höglund *et al*., 2013).

Inclusion of emissions from LUC can heavily influence CF results. Depending on method used and assumptions made, the CF can increase from a few percent to several hundred percent (Röös & Nylinder, 2013). The effect of excluding emissions from LUC on the results in **Papers I**, **II**, **III**, **V** and **VI** is briefly discussed in the next section.

3.8.2 Implications of omitting emissions from land use change

In **Papers I**, **II** and **V** cultivation on existing cropland was considered, so no emissions from dLUC needed to be accounted for. Turning to iLUC, according to the method proposed by Audsley *et al*. (2009), based on the assumption that all use of land drives LUC, the CF values would increase (*Figure 10*). Since that method attributes an equal amount of GHG emissions to all land, the increase is less for root crops and vegetables with high yields than for cereals, which have a lower yield per hectare. It should be noted that LUC modelling choices heavily affect the CF and often overshadow uncertainty arising from the uncertainty in input and other model variables.

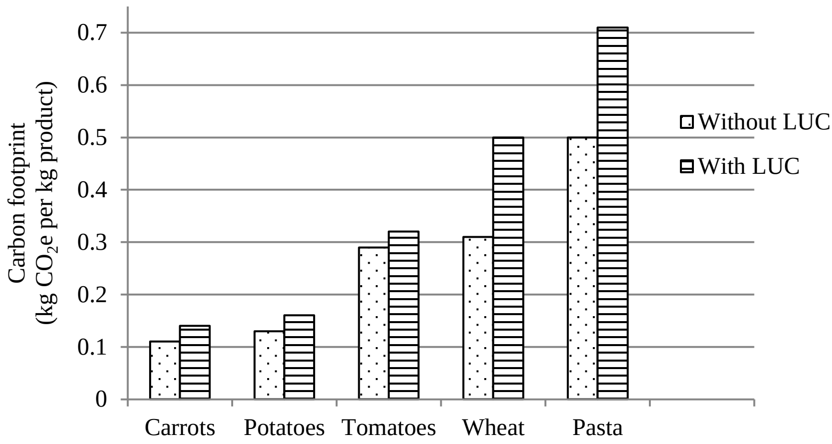

Figure 10. Carbon footprint of different food products produced in Sweden with and without emissions from land use change (LUC). Values without LUC are from **Papers I**, **II** and **V.** Emissions from LUC calculated according to the method of Audsley *et al.* (2009), in which 1.43 ton CO_2e/ha is allocated to all use of land.

The effect of including emissions from LUC on the results in **Papers III** and **V** would be highly dependent on the LUC method used and needs further research. Including emissions from deforestation when studying correlations between CF and other environmental impact categories (**Paper III**) would probably not affect the main conclusions. However, LUC that leads to carbon sequestration (section 3.3.3) would make it difficult to draw general conclusions on correlations, since the ability of soils to store carbon is highly variable.

Including emissions from LUC in the meat guide described in **Paper VI** using most LUC methods proposed would not change the evaluation of chicken, pork and beef as being ‘green’, ‘yellow’ and ‘red’ , respectively, from a climate perspective based on current commonly used feeding strategies (Röös & Nylinder, 2013), but the numerical boundaries for these colours would need to be increased. The meat guide includes biodiversity consideration of LUC as imported soy from regions where deforestation is taking place is not permitted for a ‘green’ light in the biodiversity category. This is based on the viewpoint that it is the expanding crops that cause deforestation, similarly to the methods suggested by Leip *et al.* (2010), Gerber *et al.* (2010) and Ponsioen & Blonk (2012).

4 Communicating and acting on the carbon footprint of food

One of the most obvious and straight-forward ways of communicating food CF is labelling the actual food product packages with either numerical CF values, or using easier to grasp symbols based on numerical CF, but without numerical information. Globally such labelling initiatives are plentiful and their effectiveness as a policy instrument is discussed in section 4.1. Due to several challenges associated with such labelling, communicating advice on climate smart food purchases through simple recommendations instead is discussed in section 4.2. Risks of problem shifting when acting on the CF as the only sustainability indicator are handled in section 4.3. An attempt to effectively communicate CF information on different protein sources in a meat guide while simultaneously highlighting possible trade-offs is described in section 4.4.

4.1 Carbon footprint labelling

Retailers were the pioneers in the field of food CF labelling. There are several reasons why retailers are interested in food CF: 1) to demonstrate their corporate commitment to reducing sector GHG emissions, 2) to differentiate their products and 3) to identify hot-spots within the supply chain and take measures to reduce them (Kasterine & Vanzetti, 2010). Strategies regarding the communication of CF to consumers vary between retailers. Tesco launched a grand ambition in 2007 to label all its products, while others have opted to use the results from the CF calculations internally (Olofdotter & Juul, 2008). Several different types of CF labelling schemes with varying types of labels are currently in use worldwide, although the number of individual products labelled is still low considering the multitude of products available on the market. Several organisations such as the Carbon Trust in the UK, the French Environment and Energy Agency, the PCF project in Germany, the Japanese

Ministry of Economy, Trade and Industry and the Korea Ecoproducts Institute propose use of CF information on products to help consumers take GHG emissions into account in their buying decisions (McKinnon, 2010). A review of CF initiatives performed in 2009 found 16 product CF schemes, dominated by agricultural products (Bolwig & Gibbon, 2009). In this section a few different types of labels are discussed to highlight some critical issues with different ways to design labelling schemes and to discuss the validity of CF labels as a policy instrument for reduced GHG emissions. For reviews of CF labelling initiatives see Olofdotter & Juul (2008), Bolwig & Gibbon (2009), SEPA (2010) and Quack *et al*. (2010).

4.1.1 Numerical labels

Figure 11 shows three examples of numerical CF labels. The first one, starting from the left, is the Carbon Trust label (Carbon Trust, 2013), which was used by the British retailer Tesco to label some of its products. The second one is from the Swedish hamburger chain MAX (MAX, 2013), while the third one is the label developed and used by the French retail chain Casino (Casino, 2013).

Figure 11. Three examples of numerical carbon footprint labels. From left; Carbon Trust label used by the British retailer Tesco among others, the label used by the Swedish hamburger chain MAX and a label developed and used by the French retail chain Casino.

While the Carbon Trust and MAX labels show the numerical CF value only, the Casino label also places the CF of the product on a range, hence providing the consumer with a reference system. Consumer research has indicated that this might be useful in enhancing consumer understanding of CF values. Upham *et al*. (2011) used focus group interviews to study consumer understanding of the numerical CF label of the Carbon Trust labelling scheme and found that although a majority of consumers were in favour of CF labels, they had difficulties interpreting them. Several consumers highlighted the need for more information to make the labels useful, *e.g*. a reference system similar to that for daily recommended amounts of nutrients, or some kind of scale to show whether the value presented is high or low. However, although the Casino label provides a scale, it is unclear how it should be interpreted, *e.g*. if there are different scales for different groups of food items such as milk and bread. To illustrate to consumers the choices that lead to large reductions in GHG emissions, the scale would need to be the same for all food products. Most plant-based foods would then end up on the lower half of the scale, while livestock products would score higher. However, such an absolute scale might be discouraging to consumers, as it would show little difference between different products of the same type.

Another challenge with presenting a scale is that it is quite difficult to establish the beginning and end to *e.g.* different colour shades used on the scale, which is a question of normalising GHG emissions to something meaningful. One way could be to normalise emissions to the per capita sustainable level of approximately 1 ton CO_2e per year (IPCC, 2001). However, Upham *et al.* (2011) raise several issues with such a strategy. One critical point is that few activities fit within this limit, so such a benchmark might discourage consumers. However, little is known about how consumers would be affected by such communication and more research is needed in this field. Having a few separate traffic light scales, one each for functionally comparable products, could be an interesting alternative to study in detail. For example there could be a separate scale for protein sources such as meat, fish, cheese and legumes, one for carbohydrate-rich foods such as potatoes, pasta and rice, one for vegetables and so on. The ‘meat guide’ described in section 4.4 and **Paper VI** is an attempt to develop a consumer communication tool for protein sources based on this strategy. However, due to the difficulties in establishing an absolute scale, a relative scale was used instead.

The advantage with numerical CF values is that they provide an absolute measure, which makes it possible to compare different types of interchangeable foods with each other (and also with other activities like car driving). For example, milk can be compared with other beverages such as soy and oat drink, and beef can be compared with pork and chicken, fish and plant-based ‘meat replacers’, *e.g.* soybean sausages. However, this requires all products to be labelled using the same labelling scheme to ensure that differences in CF are not due to methodological differences between labelling schemes. If all products in a purchase situation were labelled, consumers could make relevant comparisons and decisions based on the CF label without understanding the magnitude of the values presented. For example, in the case of the hamburger chain MAX (*Figure 11*), the number of items to purchase is limited and all products are labelled and directly comparable (no need to translate CF numbers due to different packaging sizes, portion sizes, emissions from preparation *etc.* as is the case for food ingredients in a supermarket, section 3.2). Hence, it is easy for consumers to see that vegetarian, fish and chicken products have a considerably lower CF than products containing beef.

Another advantage with numerical CF values are that they are in a way ‘neutral’; the number is simply presented and it is up to the consumer to judge whether it is small or large. Presenting for example a red light on highly climate impacting products might make the information easier for consumers to grasp, but retailers and restaurants might be reluctant to put such labelling on their products. Such labelling, which would signal in a very obvious way that the product is ‘bad’, would probably require legislation comparable to *e.g.* health risk information on cigarette packages.

As discussed in section 3.6, the precision with which a CF can be estimated is limited. The MAX labelling scheme uses only one and two significant digits, labelling products in kg CO_2e as 0.1, 0.3, 1.7 *etc.*, which probably correctly reflects the precision in these values. In the labelling of Walkers potato crisps approved by the Carbon Trust, one flavour was labelled 75 g CO_2e while another was labelled 76 g CO_2e. This level of precision in food CF is not possible taking into account the difficulties in CF calculations explained in Chapter 3 of this thesis and elsewhere (*e.g.* McKinnon, 2010) and might be counterproductive for reducing emissions if consumers think that they are taking an important action when choosing the package labelled 75 g CO_2e over that labelled 76 g CO_2e.

4.1.2 ‘Climate friendly’ certification schemes

Due to the complexities both from a calculation and communication perspective of numerical CF labels, several labelling initiatives have chosen not to present figures on GHG emissions, but rather to provide consumers with a choice of ‘climate friendlier’ food products. One example is the Swedish Climate Certification for Food project, which chose to develop, based on LCA, a set of requirements for reduced GHG emissions from production of different types of food. For example, there is a requirement for the use of biofuels for heating greenhouses and another regarding the maximum emissions caused by the production of mineral fertilisers (CCfF, 2013). These rules have since been incorporated into two different Swedish certification schemes, either completely in the additional climate certification of the Swedish Seal of Quality certification (SSoQ, 2013) or partly in the KRAV certification scheme for organic production (KRAV, 2013).

Certification schemes that include relevant measures to reduce GHG emissions can be effective in reducing emissions from the production of food. **Paper I** showed that when the rules from the Swedish Climate Certification for Food project were applied, the CF of potato was reduced by on average 9%.

For this reason, these labelling schemes can be preferable over pure numerical labelling schemes that do not include any reduction commitments (Upham *et al.*, 2011). However, schemes that highlight the best-in-class product within a food group, *e.g.* the 'best' beef, the 'best' tomatoes and so on, do not offer an opportunity for the consumer to choose between different types of food. Hence, even in a situation where consumers would react to these labels to a large extent, they have limited possibility to substantially lower the GHG emissions from food consumption as a whole, since they do not give consumers guidance away from high-impact foods such as meat and dairy.

4.1.3 Food carbon footprint labelling as a policy instrument

Although CF labelling initiatives are plentiful, there is little proof of the effectiveness of CF labelling of food in reducing emissions. Hence, it is relevant to question whether CF labelling of food is a good policy instrument. Stern (2008) proposes three basic principles for the design of climate change policy:

- "Effectiveness – it must lead to cuts in greenhouse gas (GHG) emissions on the scale required to keep the risks from climate change at acceptable levels;
- Efficiency – it must be implemented in the most cost-effective way, with mitigation being undertaken where it is cheapest; and
- Equity – it must take account of the fact that it is poor countries that are often hit earliest and hardest, while rich countries have a particular responsibility for past emissions."

The questions that arise from these principles as regards food CF labelling are: To what extent will consumers turn to low CF food products based on the information provided in the CF label? Will labelling food products with CF information be a cost-effective way of changing consumer behaviour? How will CF labelling affect the export opportunities of low-income countries?

When consumers are asked about their attitudes to CF labelling, polls and interviews generally show that consumers are interested in CF labels on foods but to varying extents (L.E.K, 2007; Toivonen, 2007; Berry *et al.*, 2008; Blomqvist, 2009; Gallup Organisation, 2009; Upham & Bleda, 2009; Gadema & Oglethorpe, 2011; Tan *et al.*, 2012; YouGov, 2012). A study carried out in Sweden in 2012 showed that 73% of the respondents would like to have CF labels on food and 72% said they would be willing to pay more for products which had been produced with decreased emissions (YouGov, 2012). In contrast, market research in the UK showed that only 44% of respondents would switch to a product with a smaller CF that was not their first preference and only 15-43% would be prepared to pay more for products with a lower CF (L.E.K, 2007). However, these studies have limited validity, as consumers tend to give responses that place them in a good light (Diekmann & Preisendorfer, 1998). There is also a well-documented gap between consumer attitude and behaviour whereby a positive attitude towards something, in this case purchasing low CF foods, does not translate into actual behaviour (Leire & Thidell, 2005; Aertsens *et al.*, 2009). Therefore, in **Paper IV** a critical review on the subject was performed, drawing on experiences from labelling and marketing of organic foods, rather than asking consumers for their preferences and expected behaviour. Obstacles to purchasing organic food products identified in the literature were analysed for their relevance in the case of CF-labelled foods, based on the assumption that the underlying values associated with buying organic foods (altruism, ecology and universalism) also apply to the purchase of CF labelled foods. The results are summarised in *Table 6*.

Table 6. *Obstacles to purchasing organic food, as reported in the literature (**Paper IV**)*

Obstacle	Comment	Relevance for the purchase of carbon footprint (CF) labelled foods
High price	Ranked as most important barrier by consumers	High; willingness-to-pay probably lower for CF labelled products compared with organic since CF labelled product does not give any personal benefits
Habits	Shopping for food is a low involvement activity that is strongly governed by habit, purchasing decisions are taken in just a few seconds	High; habit is a better predictor than attitudes when the habit is strong
Availability	Consumers do not search for new products on every purchasing occasion, products need to be clearly exposed	High; critical mass of products is crucial for CF labels to be meaningful
Marketing and information	Clear and reliable information is needed for consumers to act, as consumers have limited knowledge about food production	High; how to make CF information understandable to consumers is non-trivial
Lack of trust	The multitude of eco-labels could confuse consumers and decrease the trust in all labels	High; a CF label would introduce yet another type of label
Perceived consumer effectiveness	The consumer's belief that the action taken will have an effect	High; consumer knowledge of climate impact from food is limited

It was concluded in **Paper IV** that all known obstacles to the purchasing of organic food also apply to CF labelled foods. In fact, since CF labelled food does not bring any personal benefits to the consumer, which is the perceived case for organic foods, the consumers' willingness to pay a price premium for labelled products is probably lower for CF labelled products than for organic (Gadema & Oglethorpe, 2011; **Paper IV**). Hence, drawing from research on organic food purchases, there are strong reasons to question whether the positive consumer attitudes towards CF labelled food products found in consumer polls will translate into actual behaviour.

Another issue that was raised in **Paper IV** and discussed in **Paper VI** is that apart from the need of the information to be salient and legitimate in order to be useful, it also needs to be credible (McNie, 2007). Company proprietary labelling schemes such as the Casino labelling system (section 4.1.1) and industry-driven initiatives such as the Swedish Seal of Quality climate certification scheme (section 4.1.2) naturally suffer from issues of credibility and it is very important to clearly document and present all underlying assumptions.

When it comes to efficacy, that of CF labelling of food products is probably low, since CF is challenging and costly to calculate for several reasons (Chapter 3) and since its effectiveness seems to be limited. Several labelling initiatives have fallen short of their initial ambition, probably for reasons of complexity, high cost and unclear consumer reactions to CF labels (Bolwig & Gibbon, 2009).

Equity and CF labelling have also been discussed in the literature, as there are fears that low-income countries might suffer from reduced export opportunities if CF labelling is introduced (Brenton *et al.*, 2009; Bolwig & Gibbon, 2009; Plassmann *et al.*, 2010). CF labelling can be a disadvantage for small-scale producers and companies in developing countries, as CF is costly to calculate. However, CF labelling could offer companies in low-income counties with favourable climate conditions and low input production techniques a competitive position, as they could in some cases produce foods with lower GHG emissions than highly industrialised systems in colder climates, despite longer transport distances. However, this requires the CF scheme used to include all relevant inputs, *e.g.* capital goods, which is not the case in all schemes. For example, the PAS 2050 specification explicitly states that emissions associated with capital goods should not be included (BSI, 2011).

Hence, there are several reasons to be sceptical about using CF labelling of food as a policy instrument, a view shared by numerous researchers (Bolwig & Gibbon, 2009; Schmidt, 2009; McKinnon, 2010; Upham *et al.*, 2011). However, so far CF labelling of food has most commonly been discussed in the context of labelling the multitude of products provided in a retail setting, and hence enabling direct active choice of the consumer in a supermarket purchasing situation. However, there are several other ways in which CF values could be used and that could influence consumers indirectly. For example, if influential actors in the food chain, *e.g.* retailers, industry and large customers such as the public sector, use these CF values in their choice of products to procure, expose and market, these choices could reach larger groups of consumers than labelling individual food products. This is further discussed in section 5.4.

In addition, in purchase situations involving a restricted number of products, *e.g.* choosing from a menu at a restaurant, there are some indications that CF information could actually influence consumers. According to the MAX hamburger chain, the response to their labelling initiative (section 4.1.1) has been a 5% increase in low-emitting products during 2011 (CSRGuiden.se, 2011). More research is needed to confirm whether this increase can be attributed to the CF label, but the experiences from MAX are interesting and justify further investigating the effectiveness of CF in specific purchase situations.

Last but not least, as discussed in **Paper IV** and by Bonnedahl & Eriksson (2011), although CF labels might not alter consumer behaviour, they could fulfil an important task by educating consumers and other stakeholders involved in CF labelling initiatives about the climate impact of different food choices, which could lead to an acceptance of more powerful policy instruments.

4.2 Communicating carbon footprint using simple messages

Due to the challenges with CF labelling of food, as identified in **Paper IV** and by others (Schmidt, 2009; McKinnon, 2010; Gadema & Oglethorpe, 2011) and discussed in section 4.1.3, it is interesting to evaluate other means of communicating the GHG emissions associated with food production to consumers.

Since food purchasing is a low-involvement activity and consumer responses to labelling are low, it could be more effective to communicate some restricted, easy to grasp messages, which consumers could use as a rule-of-thumb when purchasing food. These recommendations could also be used by NGOs, authorities, the retail sector, the food industry and in public procurement when striving for more sustainable food consumption patterns among consumers. A survey on communication messages used among Swedish authorities and organisations in their promotion of more climate friendly food consumption (Tjärnemo & Spendrup, 2011) identified the following messages as commonly used:

- ➢ Eat less meat
- ➢ Don’t waste food
- ➢ Eat locally produced food
- ➢ Eat according to season
- ➢ Eat organic food

These recommendations are simple, but are they suitable for promoting low CF eating habits? This is discussed in sections 4.2.1-4.2.6. It should be noted that for most of these recommendations there are other advantages from an environmental and social perspective which might justify using them as advice to consumers. There are also disadvantages that need to be considered. However, here they are evaluated from a climate perspective only.

4.2.1 Eat less meat

Meat generally has a considerably higher CF than plant-based food (section 1.4). This is especially true for beef, due to the emissions of CH_4 from enteric fermentation in ruminants. However, most livestock products have a higher CF than vegetables, roots, fruits and cereals, due to the need to feed animals several times the amount of energy in feed as is returned in food products. For example, to produce 1 kg of bone-free pig meat in Sweden, 7 kg of feed are needed, while the corresponding amount for 1 kg of bone-free chicken meat is 4 kg of feed (calculated using data from Cederberg *et al*., 2009b).

When the complete Western diet is considered, it is apparent that meat is problematic from a climate perspective, since although meat commonly constitutes only around ten mass-% of the food consumed, the GHG emissions from meat production make up approximately 50% of the total GHG emissions from food consumption (Sundberg *et al*., 2013). Garnett (2011), who studied the best alternatives to reduce the GHG emissions from the food system, list reducing the intake of meat and dairy products and avoiding over-consumption of food as the most effective measures. A multitude of other studies have also highlighted the need to reduce meat consumption in the Western world, in order to lower the impact on the climate system and on other sustainability issues such as land and water use, eutrophication and biodiversity and for reasons of public health (Beddington *et al*., 2011; Foley *et al*., 2011; Foresight, 2011; Tukker *et al.*, 2011; Moomaw *et al.*, 2012; SBA, 2013; Smith & Gregory, 2013). Hence, a recommendation to consume less meat, but also less dairy, is highly relevant in order to reduce GHG emissions from food consumption.

4.2.2 Don't waste food

It has been estimated that approximately one-third of all edible food produced for human consumption is lost or wasted. In the developed world, food is mainly wasted in the consumption phase, while in low-income countries the main losses take place earlier in the food chain due to *e.g.* poor infrastructure, packaging and storage facilities (Gustavsson *et al.*, 2011). Wasting food is of course a waste of valuable resources and also contributes to GHG emissions for no reason. Hence, minimising losses is an important and sensible recommendation for reducing impacts from the food chain.

4.2.3 Eat locally produced food

Since transport makes up a great proportion of global GHG emissions, intuitively it seems reasonable to assume that consuming locally produced food is an important measure for reducing GHG emissions, as is also a common perception among consumers. Locally produced fruit and vegetables can have considerably lower CF than products which have been transported long distances, since emissions from transport can make up a substantial part of the total CF of products in these food groups (for a review of studies see Edward-Jones *et al.*, 2008). However, these savings are small when the complete diet is considered, since fruit and vegetables usually have a low overall CF compared with livestock products (Weber & Matthews, 2008). If local transport is inefficient, *e.g.* if consumers visit farm shops using private cars or if local produce is delivered by non-optimised routes in inefficient vehicles, the emissions from local products can exceed those from imported goods (Mundler & Rumpus, 2012). Hence, it cannot be stated unequivocally that local foods have a lower CF than imported products, as this depends on how the food is transported.

If local food products can be efficiently delivered to consumers, there is great potential for reduced emissions from *food transport*. However, food transport makes up a minor part of overall food sector GHG emissions (*e.g.* 12% of direct food sector emissions in the UK; Garnett, 2011), so reducing these emissions alone will not be sufficient to achieve substantial reductions. Furthermore, the term 'local foods' is ambiguous, as there is no generally accepted definition. A majority of consumers in a UK study considered food to be locally produced if it was produced in the same country as it was consumed (Edwards-Jones *et al.*, 2008). In geographically large countries, like Sweden, the distance from one distant part of the country can be substantially longer than the distance to neighbouring countries, so such a definition of local food might be counterproductive if reduced transport distance is the reason for purchasing local food.

Food products transported by air have a considerably larger CF due to the large GHG emissions from air transport (*Table 5*, section 3.7.1). Currently, only a small part of overall food transport is carried out by air, but the trend for air freight is rising (Smith *et al.*, 2005).

4.2.4 Eat according to season

As discussed in section 3.7.1, there is no single, commonly accepted definition of seasonality, which is striking considering how often this advice is given on websites providing seasonal guides and in other articles regarding environmentally friendly eating. Brooks *et al.* (2011), who studied consumer perceptions of seasonal foods, found that the most common interpretation of seasonal food refers to food that is grown, and possibly consumed, during its natural growing season without artificial heat or light. Several consumers in that survey also associated seasonal foods with locally grown foods, while others accepted foods that were grown elsewhere.

Due to the lack of a clear definition of eating seasonal, the variability in production systems and the limited research in the area, it is difficult to evaluate the validity of this recommendation. To increase knowledge, in **Paper V**, the CF of four scenarios of Swedish yearly per capita consumption of tomatoes and carrots was calculated based on four different definitions of seasonality (*Table 4*, section 3.7.1). The results are presented in *Figure 12*.

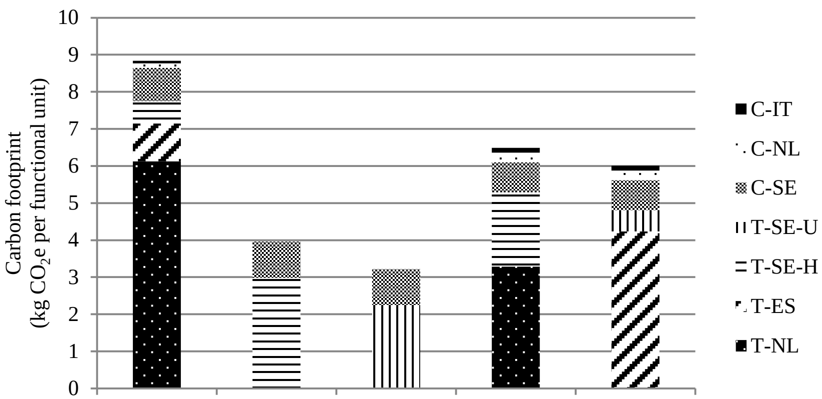

Figure 12. Carbon footprint of the Swedish yearly per capita consumption of tomatoes and carrots. In definitions A and B the geographical limitation is Sweden, but definition A allows heating of greenhouses and definition B does not. Definitions C and D both allow produce from Europe, but definition C allows use of heated greenhouses while definition D does not. C-carrots, T-tomatoes, IT-Italy, NL-the Netherlands, SE-Sweden, ES–Spain, U-unheated greenhouse, H-heated greenhouse. Functional unit is 10.4 kg of tomatoes and 9.2 kg of carrots.

Using the strictest definition of eating seasonal (definition B), which did not allow imports or heating of greenhouses, the CF for the tomatoes and carrots was reduced by 64%. When heating of greenhouses was allowed but no imports (definition A), the reduction was also substantial (55%) due to heating of Swedish greenhouses being based on biofuels. When the geographical limit was Europe but with Swedish produce favoured when available, the reduction was approximately 30% for the definition which allowed heating (C) and resulted in tomatoes being imported from the Netherlands outside the Swedish season, and also for the definition which did not allow heating (D), resulting in tomatoes being imported from Spain when not available in Sweden. Hence, **Paper V** showed great potential for reducing the GHG emissions from tomato and carrot consumption by eating seasonal according to these definitions. It should be noted, however, that for the greatest reduction potential, consumption patterns would have to be heavily modified, as tomatoes would only be consumed during three months and not continuously throughout the year as in current consumption.

Brooks *et al*. (2011) carried out case studies of different supply routes for lamb, potatoes, raspberries, strawberries and tropical fruits (melon and pineapple) at different times of the year and found that it was not possible to uniformly conclude that eating seasonal, regardless of definition (see section 3.7.1), was environmentally beneficial, as the outcome of the comparison depended on a number of local conditions which made the results for different products highly variable. Therefore, Brooks *et al*. (2011) concluded that using the recommendation 'eat according to season' in isolation is not a good criterion for environmentally sustainable food purchasing. Rather the recommendation should be to consume outdoor grown crops produced during their natural growing period (roots have considerably lower CF than vegetables grown in heated greenhouses) and to avoid crops produced with heating based on fossil fuel, which corresponds to the advice 'consume more rough vegetables' that was also found as commonly used in the survey by Tjärnemo & Spendrup (2011).

The reduction potential of between 30-60% found in **Paper V** for 36% of Swedish vegetable consumption is large in relative terms, but in absolute terms it only represents a reduction of 3-5 kg CO_2e per capita and year, corresponding to emissions from *e.g.* the production of 0.5 kg of cheese (Berlin, 2002). Taking into account that the total emissions from the food sector in Sweden are an estimated 2 tons CO_2e per capita and year (SEPA, 2008), it is clear that potential reductions due to seasonal vegetable consumption are probably limited even if they are also applied to the remaining 64% of Swedish vegetable consumption.

Hence, the recommendation on eating according to season can be valid for reducing the CF of certain fruit and vegetables, although more research is needed to establish the magnitude of this reduction and the products and periods for which it is valid. In any case, when considering the complete diet, the effectiveness of this recommendation is limited.

4.2.5 Eat organic food

Organic food and its contribution to climate change compared with conventionally produced food is another area in which it is difficult to draw general conclusions. The ban on mineral fertilisers in organic agriculture avoids GHG emissions from the production of these, but since organic production commonly shows reduced yields in comparison with conventional production this advantage is often cancelled out (FAO, 2011). However, the outcome of any comparison of the CF of organic and conventional foods is highly dependent on the type of food or crop compared, and variability between farms is generally larger than between production systems, which makes it challenging to draw general conclusions. In addition, due to the large uncertainties in methods to estimate *e.g.* N_2O emissions from soil, CH_4 emissions from enteric fermentation and GHG emissions from manure handling, large differences are needed between the CF of organic and conventional products in order to draw any solid conclusions (Cederberg *et al.*, 2011).

Soil carbon sequestration (section 3.3.3) has to date not commonly been included when comparing the CF of organic and conventional products. However, since soils under organic management have been shown to have a higher content of organic matter on average (FAO, 2011), including these changes could be beneficial for organic products from a climate perspective (*e.g.* Halberg *et al.*, 2010). However, methodological development is needed as regards estimating soil carbon sequestration and including such changes in CF calculations (FAO, 2011; section 3.3.3). In addition, since organic production generally requires more land than conventional production to produce the same amount of food, it could be argued that the alternative use of this land must also be included in the comparison (section 3.2).

Hence, the recommendation to turn to organic foods in order to lower the CF is doubtful, due to high variability in management practices within organic and conventional production and the uncertainty in models accounting for soil emissions and carbon sequestration. For a more comprehensive review on the subject, see Röös *et al.* (2013).

4.2.6 Evaluation of the recommendations

To influence consumer behaviour, messages need to be clear and simple. The messages presented and discussed in this section are simple, but at second glance not all of them are clear, as definitions of *e.g.* locally produced and seasonal food are lacking. While ‘eat less meat’ and ‘don’t waste food’ are pieces of advice that are scientifically valid, there is nothing in the literature to show that following the advice to ‘eat locally produced food’, ‘eat according to season’ and ‘eat organic food’ would lead to reduced GHG emissions from food consumption in general. That said, GHG emissions from food transport are problematic. Nearly 20% of the transport in the EU involves transport of food and agricultural products (Eurostat, 2011) and the emissions from such transport also need to be reduced. When it comes to heating of greenhouses, it is questionable whether using biofuels for this purpose is a wise use of this renewable energy source, or whether it would be better utilised in the energy sector. Consequently, consuming out-of-season produce which requires high amounts of energy input could be questioned as a whole in a future low CF food system, if this energy is not provided from waste heat that cannot be used for other purposes.

However, for large reductions here and now, it is important to rank different recommendations according to their effectiveness. If they are all presented as equally important, there is a risk that consumers will turn to the recommendation that is most convenient for them. Since consumers demand locally produced and seasonal foods for several other reasons than environmental concern (Weber & Matthews, 2008; Brooks *et al.*, 2011), there is a risk that consumers will feel content with such actions and not focus on the most important recommendations.

Another question is whether there are other messages that have not commonly been voiced, but that should be added. Garnett (2011) listed measures to reduce GHG emissions from the food chain according to priority and identified two actions as high priority; consuming less meat and dairy products, as discussed above, and an action that is seldom discussed, namely ‘eat no more than needed to maintain a healthy body weight’. Naturally, over-consumption means that foods that are not really needed (or needed elsewhere) are produced, causing GHG emissions in vain, just as for wasted foods. However, the climate impact of over-consumption is highly dependent on the form. If it is mainly in the form of sugars and carbohydrates, it is less of a problem than if it is dominated by meat and dairy. Other actions listed by Garnett (2011) include saving energy in food preparation, shopping on foot and tolerating foods of lower quality, as well as consuming less products with a low nutritional value, such as coffee, tea, alcohol and chocolate. These are important measures that deserve more attention, but when prioritising resources for information campaigns and designing other policy instruments, the focus needs to be on the measures with the greatest potential to reduce emissions.

4.3 Risk of problem shifting

The major threat that has been raised as regards using and acting on CF information is the risk of problem shifting, as only one impact category is used to indicate the sustainability of products, although it is known that consumption of products and services affects the environment in several different ways. How serious is this risk, especially in the case of food?

Paper V mentions the increasing risks of water stress, pesticide leakage and nutrient run-off if production of tomatoes is concentrated to locations with favourable climate conditions in order to avoid the need to heat greenhouses, hence reducing GHG emissions from energy use. Laurent *et al*. (2012) studied how the CF of approximately 4000 products and services in the Ecoinvent database correlated to a wide range of environmental aspects and found that, in general, the CF showed a high correlation with most other impact categories. However, several areas that risk being in conflict with the CF were identified, including toxicity, depletion of resources and land use. Pollution swapping as regards GHG emissions in agricultural production has been studied by several authors, *e.g.* Novak & Fiorelli (2010) discussed trade-offs between GHG and ammonia emissions, Rugani *et al*. (2013) highlighted the possible conflict between CF and the use of chemicals, Page *et al*. (2012) found a trade-off between CF and water use and Verspecht *et al*. (2012) summarised several potential trade-offs and co-benefits from GHG mitigation measures in agriculture. **Paper III** provided more knowledge on the subject by evaluating the suitability of using CF as an indicator for the wider environmental impacts of meat production (section 4.3.1). The impact categories included in the study in **Paper III** were those commonly included in existing LCA studies on meat. There are also other impact categories, environmental, social and economic, that deserve attention. Two of these which are highly relevant to food production are briefly discussed in sections 4.3.2 and 4.3.3, namely synergies and conflicts between CF and animal welfare, and between CF and impacts on biodiversity.

4.3.1 Carbon footprint as an indicator for meat production

In **Paper III**, the correlation of CF to eutrophication potential, acidification potential, primary energy use, land use and toxicity (pesticide use) was analysed using data from 53 LCA scenarios of production of beef, pig and chicken meat. The results showed that for meat production from monogastric species, there is little risk of jeopardising other impact categories, since most impact in all categories is related to feed production. Hence, if less feed is needed to produce meat, the environmental burden is less. However, there is a risk that mitigation options to reduce ammonia emissions (which lead to acidification and eutrophication) from manure handling will increase the CH_4 emissions, and hence the CF, especially in warm climates. Furthermore, if feed that causes less GHG emissions during cultivation is used to lower the CF of meat and this feed is less appropriate for the animal, more nitrogen could be found in manure, causing an increased risk of acidification.

For beef the situation is more complicated. Beef production relying on grazing on natural and semi-natural grasslands can be very energy-efficient and cause little toxicity impact, since small amounts of energy and pesticides are needed for pasture management, but may still cause large GHG emissions due to CH_4 emissions from enteric fermentation (Cederberg & Nilsson, 2004; Cederberg *et al.*, 2009a). However in some cases, pasture-finished beef production can require more energy than feedlot-finished systems owing to high impacts from production of winter feed and high throughput volumes (Pelletier *et al.*, 2010). In addition, ruminant systems often require much land for feed production. Although CF has been proven to be correlated to land use, a simple measure of the area (m^2*year) used in studies included in the evaluation does not provide a complete picture. Since different types of agricultural land are suitable for different purposes, they should be valued differently. For example, if beef production is carried out on land not suitable for arable farming, this is a land-efficient way of producing meat, despite the land area use being high compared with a system in which feed is produced on arable land. The results from **Paper III** are summarised in *Table 7*.

Table 7. *Carbon footprint of meat as an indicator of wider environmental impact. 'Yes' means the carbon footprint can function as an indicator for the environmental impact category, 'No' means that it cannot function as an indicator for that category*

	Primary energy	Land use	Acidi-fication	Eutro-phication	Toxicity[a]
All types of meat	**No**	Yes	Yes	Yes	**No**
Meat from monogastric animals	Yes	Yes[b]	Yes, with restriction[c]	Yes	Yes, with restriction[d]
Meat from ruminants	**No**	Yes	Yes, with restriction[c]	Yes	**No**

[a] Pesticide use

[b] Except for free-range systems

[c] Possible conflict across liquid/solid manure handling systems, especially in warm climates, and for feed exchange strategies with differing nitrogen efficiency in the animals

[d] Only across conventional systems with regulated pesticide use and not for organic systems that do not use synthetic pesticides or mineral fertilisers

4.3.2 Synergies and conflicts with animal welfare

A unique feature of livestock systems that distinguishes them from crop production and industrial production systems is that they involve living, sentient beings. Hence, the aspect of animal welfare cannot be omitted when designing sustainable livestock systems. Healthy animals which produce meat, eggs and milk efficiently are favourable both for low CF and for animal welfare, while access to pasture and outdoor runs can increase feed consumption and hence increase CF. Breeding for fast growth and high yield decreases the CF of livestock products, but has health implications, *e.g.* leg problems in several animal species. Methods for incorporating animal welfare aspects into LCA have been discussed, but have not been used to date (Blonk *et al.*, 2010). Röös (2011a) found that for pig meat, generally, systems with higher space allowances and access to outdoor runs, *e.g.* organic production, showed higher CF values. Hence, there is a risk that a focus on low CF values can conflict with animal welfare aspects, why animal welfare was included as one indicator in the 'meat guide' described in **Paper VI**.

4.3.3 Carbon footprint and biodiversity

Biodiversity is commonly used as a safeguard subject (area that society wants to protect from degradation and that is influenced by many environmental impacts) in LCA rather than a midpoint impact category describing one type of environmental damage, such as CF, acidification and eutrophication potential. However, in Sweden environmental issues are structured into 16 environmental quality objectives, one of which targets the preservation of species ('A Rich Diversity of Plant and Animal Life'), while other objectives include 'Reduced

Climate Impact', 'Zero Eutrophication' and 'Natural Acidification Only'. Hence, in Sweden the objective for biodiversity is often contrasted against the objective for reduced climate impact, especially in the case of beef production on semi-natural grassland, in which the animals help preserve biodiversity by keeping the grass short (LRF, 2009), and in the comparison of organic and conventional production, since pesticide use can lead to reduced biodiversity, but to higher yield and therefore potentially lower CF of the products produced. Therefore, it is interesting to discuss how CF and impacts on biodiversity are related (**Paper III**).

The subject of biodiversity is large and complex, as it includes diversity at gene, species and ecosystem level. In addition, the impact on biodiversity from different types of land use varies considerably depending on the original habitat type, production intensity and surrounding landscape (Henle *et al*., 2008). Globally, a major threat to biodiversity is deforestation (MEA, 2005; UCS, 2011). One can argue that producing food on less land will 'spare land' and hence biodiversity. Using less land usually also means lower CF, so on a global scale producing meat and food/feed more CF efficiently would also save biodiversity. Although this line of reasoning is widely used (Green *et al*., 2005; Steinfeld *et al*., 2006), some authors propose an alternative strategy in which land is 'shared' rather than 'spared', where sharing refers to combining agricultural production and nature conservation (Vandermeer & Perfecto, 2006; Fairlie, 2010). It is also questionable whether land will ultimately be 'spared' by more intense production, or whether intensive production will just spread out on all land, taking the global demand for food and fuel into account (Garnett, 2011).

Due to the difficulties in measuring the complex concept of biodiversity, there is currently no commonly applied method for explicitly quantitatively incorporating biodiversity impacts from land use into LCA, although several interesting and promising initiatives are being developed (Koellner *et al*., 2013). Hence, in the 'meat guide' described in **Paper VI** and in section 4.4, qualitative criteria for biodiversity were developed rather than quantitative criteria. The criteria build on both the need to graze and conserve semi-natural pastures ('share land'), and the notion that the most important driver of biodiversity loss is land conversion from a natural state to human use ('spare land') (MEA, 2005).

4.4 Communicating carbon footprint and highlighting trade-offs

The CF of food products must be communicated effectively (section 4.1.3), while at the same time avoiding the issue of problem shifting (section 4.3). An attempt to tackle this enormous challenge was made in an interdisciplinary project from a LCA perspective and a communication perspective simultaneously, in the development of a science-based 'meat guide' (**Paper VI**). Meat was chosen since this product group dominates the GHG emissions from a typical Western diet. Since various studies have highlighted the need to decrease meat consumption in the Western world and not only to eat more sustainably produced meat (section 4.2.1), alternative sources of protein (game meat, eggs, cheese and plant-based alternatives) that could replace livestock meat were also included in the guide.

4.4.1 Design of the meat guide

The guide was developed based on seven requirements that were established at an initial interdisciplinary workshop, *e.g.* that products should be evaluated from a life cycle perspective and that the guide should give guidance based on the CF, but also other environmental parameters and animal welfare considerations (**Paper VI**). Since it is known that to succeed in consumer communications it is important that the message is targeted (Pickton & Broderick, 2005), one of the requirements on the guide was that it should be aimed at a specific group of consumers. It was decided to target the guide towards those consumers who express a high level of concern but do not see how they can make a difference and therefore do not take much action, referred to here as the 'interested consumers'. Due to the crucial role of the retail sector in enabling a sustainable food system (**Paper IV**; McKinnon, 2010) an equally important target audience for the meat guide was food professionals in the retail sector.

Based on the results from **Paper III** and Röös (2011a) and discussions with experts and representatives from the industry and the retail sector, impacts on biodiversity, the use of pesticides and animal welfare were chosen as indicators in addition to CF, since these risk coming into conflict with the CF (section 4.3). For each indicator, criteria for three levels of environmental or animal welfare 'harm' were developed on a relative scale, hence describing best and worst in class, rather than using absolute sustainability thresholds, which are difficult to define (section 4.1.1). Data on CF, biodiversity impacts, use of pesticides and animal welfare aspects for the product systems included in the guide were collected. Using these data, criteria were developed with the aim of differentiating between different types of products (*Table 8*).

The well-known and commonly used traffic light system of green/yellow/red light was used to symbolise the three levels, since studies have shown that consumers prefer the traffic light system to numerical information and other labels with different types of text or logos (Berry *et al*., 2008; Upham *et al*., 2011).

Table 8. *Summary of the criteria used in the Swedish meat guide (see* ***Paper VI*** *for background to these)*

	Green	Yellow	Red
Carbon footprint	Carbon footprint less than 4 kg CO_2e/kg	Carbon footprint between 4-14 kg CO_2e/kg	Carbon footprint larger than 14 kg CO_2e/kg
Biodiversity	Positive contribution to the conservation of endangered species by grazing of semi-natural pastures **or** products that can be produced in less than 5 m^2 *year of agricultural land per kg of edible product.	No use of soy from South American **or** organic production (higher biodiversity in the agricultural landscape), **or** use of South American soy but land use less than 5 m^2*year per kg of edible product.	Uses South American soy. Demand for soy might drive deforestation with large negative impacts on biodiversity in South America
Use of pesticides	No use of synthetic pesticides	Use of synthetic pesticides in feed cultivation less than 1.5 g of active substance per kg edible product produced.	Use of synthetic pesticides in feed cultivation exceeding 1.5 g of active substance per kg edible product produced.
Animal welfare	Covered by Swedish animal welfare legislation or equivalent **and** allowed to graze outdoors.	Covered by Swedish animal welfare legislation or equivalent **or** grazing at least half the year and stunned before slaughter.	Others

4.4.2 Evaluation of the meat guide

As can be seen from the picture of parts of the meat guide in *Figure 13*, the guide gives no clear answer on which meat type is preferable. Meat from ruminants suffers from high CF, while pork and chicken suffer from high impacts on biodiversity and high pesticide use due to their dependence on soy as feed. Although the guide contains many simplifications, it still provides considerable amounts of information that allow a deeper understanding of the underlying origins and causes of environmental impacts from livestock production, to which the target audience is presumably receptive. For example, it can be seen that there are substantial differences between different production systems for beef meat, with animal welfare-friendly, pasture-based beef production receiving three green lights and one red for CF.

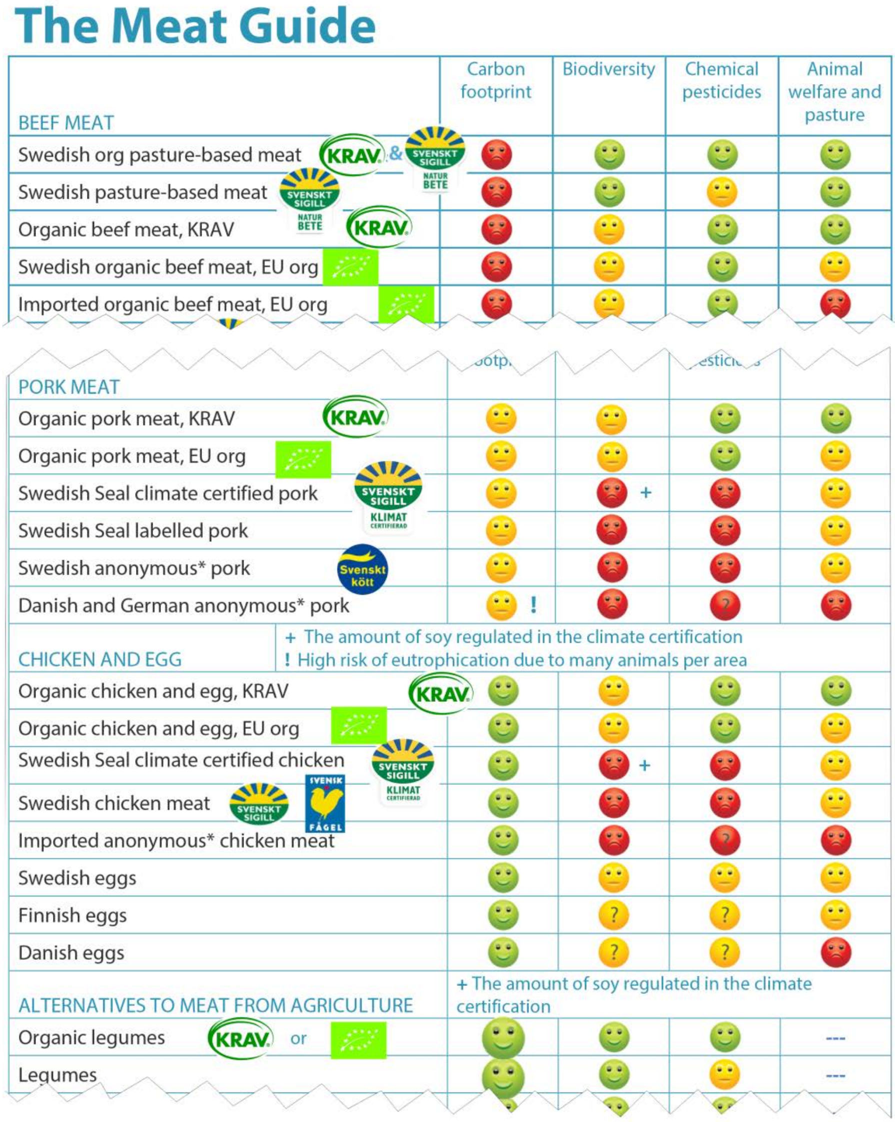

Figure 13. Parts of the meat guide discussed in **Paper VI**.

Many consumers have spontaneously got in touch with us to praise the meat guide for summarising the different types of impact of protein production in one place, and for providing what they perceive as objective information. However, consumer research is needed to evaluate whether this indication of usefulness can be generally proven, the type and amount of consumers for which it applies and whether the guide influences consumer attitudes, intentions and behaviour. Such research is planned in future projects.

An advantage with the meat guide is that it enables and encourages consumers to choose across product categories and types, and not only within a particular product category, and that it includes not only many different types of meat but also alternative sources of protein. However, there is an obvious risk that the information in the meat guide is still too complex for the interested consumer, due to the strong habits governing food purchases (**Papers IV** and **VI**), so it is probably most useful to professionals in the food sector.

When it comes to environmental assessment aspects, the meat guide has several limitations. All indicators are given equal weight, although the CF indicator acts as a proxy for several other impact categories, which gives organic products a benefit by scoring high on both the biodiversity and use of pesticide indicator. This is unfortunate, as it could strengthen the general misconception among some consumers that organic production is the answer to achieving sustainability in the food sector, when in fact organic production shares several of the same environmental challenges as conventional production. In addition, the CF here acts as a proxy for the impact categories of eutrophication and acidification. While this works for the eutrophication and acidification *potential* (**Paper III**), *i.e*. considering the amount of eutrophying and acidifying substances emitted, site specific conditions heavily influence the actual impact that these pollutants cause, which is not reflected in the criteria of the guide. For meat from countries with generally high stocking densities the risk of high eutrophication effects is highlighted with an exclamation mark.

For the biodiversity and animal welfare indicators, the criteria are not developed from a life cycle perspective and do not relate to the functional unit of 1 kg of product, which was the initial ambition. This should be improved in future versions of the meat guide, building on methods and data that have been presented recently (Blonk *et al*., 2010; Koellner *et al*., 2013). The pesticide indicator should also be improved, since comparison using only the amount of active ingredient is a very coarse metric.

The design of the criteria for the different indicators and the choice of the indicators naturally involved subjective judgements, but all underlying assumptions are openly presented on a website (Köttguiden, 2013). Therefore although there might be different opinions as to how the criteria should be developed and how different production systems should be valued, the guide can function as a basis for discussion and raise awareness of the issues related to livestock production, which was one of the requirements identified initially.

5 General discussion

The CF methodology shares several of the advantages of a full LCA. One such advantage is the ability to compare products that are functionally equivalent, but which have been produced in different systems, *e.g.* the CF of meat (a protein source) can be compared with that of fish (another protein source). Another advantage is the consideration of the full life cycle, which avoids problem shifting between different life cycle stages. Quantitative measures of environmental impacts make them concrete and tangible.

As an environmental indicator needs to be used in order to be successful, the greatest advantage of CF is perhaps the interest it has generated among companies, authorities and organisations. Weidema *et al*. (2008a) attributes the interest in CF to the concept being ‘catchy’, easily grasped and easily put in context. For example, emissions from one activity can be directly compared with emissions from other completely different activities or yearly per capita emissions, *e.g*. emissions from meat consumption by the average Swede amount to approximately 0.7 tons of CO_2e, or about 7% of total Swedish per capita emissions from consumption, or more than half the yearly sustainable per capita emissions allowance of 1 ton of CO_2e (IPCC, 2001). Emissions from food can also be compared with those from other activities, *e.g*. consuming 1 kg of pork meat corresponds to driving approximately 40 km by car. However, influencing consumers in a purchasing situation in a supermarket by communicating the CF of food is still highly challenging. A general discussion of this is provided in section 5.1.

While food CF is simpler to calculate than doing a full LCA, it is still quite challenging due to the difficulties in measuring GHG emissions from the biological systems involved and the great variability in agricultural systems, so uncertainties must be considered. Reflections on this are given in section 5.2. The aspect of only including one impact category has also been cited as the greatest disadvantage of using CF as a sustainability indicator; see section 5.3

for more on this topic. Section 5.4 discusses situations where the CF can be highly usable and outlines some possible ways forward for food CF.

5.1 Consumer perspectives

Relying solely on consumer choice based on the communication of CF labels to consumers in a retail setting does not seem to be a successful strategy for drastically reducing GHG emissions from the food sector. This conclusion was drawn in **Paper IV** and is supported by several other authors (section 4.1.3). Price, taste and quality are the most important attributes to most consumers when purchasing food, while environmental aspects are highly relevant only to a minority of consumers. Consumers buy local food for reasons other than reduced transport (Edward-Jonas *et al.*, 2008) and they buy seasonal foods predominantly for reasons of taste and freshness (Brooks *et al.*, 2011). In addition, shopping for food is a low involvement activity strongly governed by habit, which makes it difficult for CF labels to catch the attention of consumers in a supermarket. Furthermore, it is questionable whether the current design of labels would be understood by consumers. However, the MAX hamburger chain example discussed in sections 4.1.1 and 4.1.3 indicates that there may be situations, *e.g.* when choices are limited and more time is spent on the purchase decision, in which consumers actually react to CF information.

However, consumers can be influenced in several other ways than through CF labelling of individual food products. Industry and retailers have a great possibility, and therefore great responsibility, to choose which products are presented to consumers and how these are priced and marketed. Apart from choice editing their range of products, industry and retailers could also work actively to develop and promote new and attractive alternatives to meat and dairy (the most climate impacting products), and avoid having high-impact products on sale. Furthermore, they could require their food suppliers to take active measures to reduce their on-farm emissions, in which case certification schemes like the Swedish Seal of Quality climate certification (section 4.1.2) could be valuable.

Generally, there has been overconfidence in consumers' willingness and possibility to act on environmental information. Modern society is extremely information-intense and consumers face an obvious risk of information overload (Eppler & Mengis, 2004). Keeping up to date on the latest regarding sustainable food purchases requires considerable amounts of time and effort, and such considerations have to be weighed against aspects such as price, taste, quality, nutrition, convenience, social expectations *etc*. Add to that purchasing decisions regarding electric appliances, transport, insurance, information services, clothing, toys, hygiene products *etc*. and it becomes obvious that industry, authorities and retailers cannot put all responsibility in the lap of the consumer. This is also why it was decided that a major target audience for the 'meat guide' in **Paper VI** should be food professionals in the retail sector, who can act on the information in the guide and influence consumers by measures that are more effective than labelling, *e.g*. marketing and pricing. Hence, CF can be highly valuable for decisions taken at the level of manufacturing, retail and private and public food service providers.

Due to the low effectiveness of information provision as an instrument to change consumer food purchasing behaviour, there has been a call for financial instruments (SBA, 2013). Sweden has had a CO_2 consumption tax on fuels since 1991, so it is not unreasonable to suggest that food should also be taxed according to its GHG emissions. CF information and labelling could serve an important purpose by creating a general acceptance for more powerful policy actions. To design a tax on food that is effective, efficient and equitable and to avoid problem shifting, more research is needed. However, without some strong financial steering, GHG emissions from food consumption will most probably not decrease at a rate corresponding to climate goals.

5.2 Uncertainties

From section 3.6, in which uncertainties and variations in food CF are described, it is easy to get the impression that food CF calculations are so uncertain that the results are verging on useless. However, that is not the case, as these calculations have greatly increased knowledge when it comes to the environmental impact of food products. Although CF are uncertain, without performing quantitative estimates of the GHG emissions from different types of food production systems, it is highly likely that more intuitive beliefs and perceptions would govern decision making amongst consumers, industry and policy makers, *e.g*. that grazing animals are more 'natural' and hence less environmentally harmful than animals in more industrial systems, or that emissions of GHG from food are dominated by emissions related to packaging rather than emissions from cultivation.

It must be stressed, however, that the CF of a food product is an *estimate of the magnitude of GHG emissions under the conditions formulated in the study*. A CF value should not be presented as a single value and especially not to several significant figures. Ultimately, as for all LCA results, it should be presented together with results from relevant uncertainty and sensitivity analyses. However, this is not possible in most choice situations involving consumers and food, so a more pragmatic approach has to be adopted and the risks of doing so managed.

Are the CF uncertainty ranges found in **Papers I** and **II** small or large? The answer depends on the purpose of the CF. If the purpose is to compare products from different farms, the uncertainty range is large and such a comparison is difficult, above all due to the large uncertainty associated with N_2O emissions from soils. Raising the perspective and comparing the King Edward potatoes from Östergötland (CF 0.10-0.16 kg CO_2e per kg) in **Paper I** and the pasta from Skåne (CF 0.45-0.52 kg CO_2e per kg) in **Paper II**, due to the non-overlapping uncertainty intervals given, it can be concluded that 1 kg of raw potatoes causes less GHG emissions than 1 kg of dry pasta (assuming that major model uncertainties are covered by the IPCC uncertainty ranges for N_2O emissions and emissions from LUC are similar for the two or insignificant). However, whether potatoes are preferable to pasta as a source of carbohydrates depends on portion size and losses and emissions from post-retail stages such as preparation and waste management (section 3.2), illustrating the complexity in comparing different food products based on their CF, even when uncertainty in pre-retail stages is included.

The large uncertainty in N_2O emissions from soil overshadowed most other uncertainties and rendered it impossible to increase precision substantially by collecting data on on-farm parameters other than yield and amount of nitrogen fertiliser used (**Papers I** and **II)**. The development of better methods for estimating N_2O emissions will increase the knowledge about the causes of N_2O emissions and how they can be reduced. However, it is unlikely to increase the precision in general food CF values, since yearly variations can be as large as the IPCC uncertainty intervals used in **Papers I** and **II** (Röös & Nylinder, 2013).

When it comes to GHG emissions from iLUC, it is unlikely that they can ever be quantified with a high degree of certainty due to the high complexity in the processes driving global deforestation and the fact that iLUC cannot be observed and therefore models not directly verified. Emissions due to dLUC can be observed and are easier to measure, but using these measurements of GHG emissions in LCA studies is associated with several methodological challenges, *e.g.* amortisation of the emissions over a period of time, which is an arbitrary choice. More research will help increase understanding of the processes and drivers behind deforestation and use of more standardised methods to include LUC in the CF of food will make it easier to compare results between studies. Future research also needs to address effects on the climate system from decreased evapotranspiration, aerosol formation and changes in albedo, since the climate effects from these phenomena can be substantial (Höglund *et al*., 2013).

Caution is needed so that uncertainties in LCA results are not deliberately used to slow down regulation or policy instruments that might limit growth in a specific sector, as has been the case in regulation of tobacco use and GHG emissions (Mattila *et al*., 2012). Food CF are uncertain, but they do provide important knowledge. Relevant uncertainty and sensitivity analysis will reveal whether solid conclusions can be drawn or not.

5.3 Problem shifting

The subject of pollution swapping or, more generally, problem shifting, including not only pollutants but also economic and social aspects, has been on the research agenda for some time, but is rarely included in policy making (Stevens & Quinton, 2009). Pollution swapping in food production is an issue of high relevance, as food production affects the environment in so many different ways (EC, 2006). Indeed, several risks of increasing impacts in other areas when choosing low CF products have been identified (**Paper III**; section 4.3). For impact categories for which there are characterisation methods that are commonly used and well understood, *e.g*. eutrophication and acidification, the risk of pollution swapping and its magnitude can be evaluated. However, while numbers are very useful for putting the focus on an issue and making it tangible, there is a risk that impact categories which are more difficult to quantitatively evaluate may be overshadowed, *e.g*. biodiversity, toxicity aspects and animal welfare. With the development of life cycle sustainability assessment (LCSA) in the field of LCA, the importance of including social and economic aspects too has been highlighted, making CF even more limited in comparison.

So does the risk of problem shifting mean that turning back to full LCA is necessary? For systems which we know little about this is probably true, while for products that have been well-studied, a more pragmatic approach could be used in which the focus is on the impact categories which risk being in conflict with decreased GHG emissions, while the CF can act as a proxy for the impact categories that will benefit from mitigation strategies for reduced CF and/or consumption of low CF products, *i.e*. the strategy chosen in the 'meat guide' (**Paper VI**). Such an approach communicates the CF of different products, while highlighting the risks of problem shifting. A major challenge of this approach is how these indicators should be weighted, *i.e*. the CF, which represents several impact categories, and a the others that only 'speak for themselves'.

Evaluation of different types of environmental indicators involves drawing the line somewhere between 'detail and completeness' and 'overview and comprehensiveness'. It is in the nature of science to be sceptical about generalising and using indicators that work well in most cases, but not all. However, there is also a need to consider how results from science can reach out to society, and to identify and propose ways to manage the risks of using indicators that can influence consumers and other influential actors in the food sector. Hence, the risk of damaging other environmental areas when acting on CF must be weighed against the risk of neglecting to act on global warming by failing to exploit the current market momentum of CF.

5.4 The way forward for food carbon footprint

Food CF are most probably here to stay. Although labelling individual food products with their CF values in supermarkets is not the most pressing issue right now, CF values are needed and are already in use in a multitude of other applications. On-line carbon calculators, which are internet-based tools for calculating the climate impact of the activities of individuals (Amani & Schiefer, 2011), need these numbers to be able to include GHG emissions from food consumption. The interest in assessing the climate impact of food in the public sector is great in Sweden, and the CF numbers summarised in Röös (2012) have been incorporated into software solutions for public procurement to facilitate such assessments (DKAB, 2013). CF values are also used for calculating the climate impact from meals and diets in research and practice (Sundberg *et al*., 2013), and when developing dietary advice (NNR, 2012). In addition, for developing financial policy instruments, *e.g.* GHG tax on food (Wirsenius *et al*., 2011), CF values of food will be indispensable.

CF calculations are also highly needed on the production side. For example, when designing labelling schemes that promote improved production (section 4.1.2) or setting requirements on low GHG emissions from the production of food in public procurement, the requirements need to be based on solid CF calculations. In addition, more knowledge about the GHG emissions from several of the existing food production systems is needed, and there is also a great need to assess the GHG emissions of new production technologies, systems and products as they emerge.

Therefore, calculation methods and standards need to improve. Meinrenken *et al*. (2012) calls for research to broaden into more practical applications and proposes a method for fast CF calculations. Several ways of simplifying CF calculations are possible, *e.g.* basing them on category rather than product level and focusing on the most GHG intensive activities, as well as using established data inventories for data collection and specialist software to facilitate calculations (McKinnon, 2010). Curiously, the British retailer Tesco, the pioneer in food CF labelling which later dropped CF numbers from its products, has just recently used a software tool to calculate a simplified CF for all its products and promises swift action on the results (Guardian, 2013). If this intention turns into firm action, the company deserves congratulation.

As discussed in sections 4.1.1 and 4.1.3, there are some specific situations when CF information on the actual food product could function for consumer communication. With improved assessment methods, the costs of calculating the CF could be reduced, making large-scale uptake at least economically feasible in the future. However, the question of communication remains. One fact that needs to be kept in mind is that different actors and situations need different types of information. While detailed numbers might function, and might even be necessary, in business-to-business communication, in low involvement purchase situations by non-professionals, information needs to be more simple and graspable. In addition, consumers are a very heterogeneous group; while some spend minutes carefully evaluating a complex flora of aspects in every purchase situation, most are governed by habit only. More research on how to communicate CF information at different levels is needed.

One issue that also needs addressing is the aspect of normalising emissions to some scale, some other activity or threshold level. In the 'meat guide' (**Paper VI**), a low CF was considered to be emissions below 4 kg CO_2e/kg product and a high CF emissions above 14 CO_2e/kg product, while a medium CF fell between these two limits. The limits were based on how different products could be differentiated from each other, but otherwise it was an arbitrary choice. Other publications have chosen other limits, *e.g.* the Nordic Nutrition Recommendations define low emitting products as those with emissions below 1 kg CO_2e/kg product and high emitting products as those with emissions above 4 kg CO_2e/kg product (NNR, 2012), which is also an arbitrary choice. It would be preferable to use some kind of reference system against which to normalise emissions. One way could be to relate emissions to the sustainable emissions allowance of approximately 1 ton CO_2e per capita and year defined by IPCC (2001), but that has some limitations, as discussed in section 4.1.1. Zhao *et al.* (2012) suggest a scale generated based upon the products ratio to the annual national GHG emissions per gross domestic product. More novel thinking and further research is needed in this area.

Finally, it can be concluded that food CF should be viewed primarily as a tool for professionals in the food sector rather than consumers. These professionals include people with influential positions in farming, industry, certification organisations, authorities, universities, retail, restaurants and catering establishments and have the power to influence a large number of consumers by the choices they make and the actions they take. As an example, Gössling *et al*. (2011) noted that food service providers have the power to influence what is eaten through the three Ps; purchasing, preparation and presentation. Purchasing is about choosing what raw material to procure. The list of CF values developed as part of this project could be of help in high-level screening during procurement (Röös, 2012), while climate certification initiatives like the Swedish Seal of Quality (section 4.1.2) can be used as a second step to ensure that farmers are taking mitigation action. Preparation deals with choice editing in meal composition, for example meat can be the side component rather than the core element of the meal, and waste can be reduced by careful planning. Presentation is about how food is presented to consumers, which could heavily affect their behaviour, *e.g.* a buffet might encourage consumers to eat and waste more, while in a retail setting placing low CF food in a central position can stimulate its purchase. Large-scale consumer action on CF information cannot become reality without such help from other actors in the food chain.

6 Conclusions and perspectives

6.1 Main conclusions

The main conclusions that can be drawn from this thesis are that:

- The uncertainty in food CF arises from high variability in management practices and site- and time-specific conditions, as well as high uncertainty in the methods used to calculate CF, especially assessments of soil emissions/sequestration and emissions due to land use change.
- Crop yield and the amount of nitrogen fertiliser applied are parameters with a major influence on the CF of roots, cereals and open-air vegetables. For vegetables grown in heated greenhouses, the yield and the type and amount of energy needed for heating are crucial.
- The uncertainty in the CF of potatoes and wheat arising from spatial, temporal and management variability and uncertainty in calculation methods, excluding indirect effects, estimated for a well-defined geographical area in Sweden, is in the range ±10-30%. This indicates that the CF uncertainty for more complex foods and foods with a more unspecific origin is considerably higher.
- Collecting more data from the farm than the most influential parameters only marginally increases the precision of the CF of roots and cereals due to large uncertainties in current calculation methods, especially methods to calculate N_2O emissions from soils.
- Variation in the published CF of meat is high due to differences in management practices and calculation methods. The CF varies between 2-5 kg CO_2e per kg bone-free meat for chicken, 4-9 kg CO_2e for pork and 11-51 kg CO_2e for beef. These values do not include emissions due to land use change, which would increase the numbers but not alter the ranking of chicken, pork, beef based on current average Swedish feeding strategies.

However, if sequestration of carbon in soils is high, the CF of certain meat could potentially be reduced.

- Focusing on low food CF values risks creating conflicts with other environmental issues such as biodiversity conservation, use of water and pesticides.
- For meat from monogastric species, in most cases the CF functions as an indicator for land, energy and pesticide use, as well as for acidification and eutrophication potential, but for ruminant meat there are possible conflicts with biodiversity, energy and pesticide use. Conflicts with animal welfare must also be considered for all species.
- Information about the climate impact of different food products is a prerequisite for consumer power. However, based on the experiences from sales of organic products, presenting CF information on product packaging as CF labels alone cannot be expected to change consumption patterns to an extent that justifies the current cost of calculating and displaying CF values.
- Known obstacles to the purchase of organic foods apply to the purchase of CF labelled foods to an equal or greater extent, since CF labelled products do not bring any personal benefits to the consumer, unlike the perceived case for organic products. Such obstacles include perceived high price, strong habits governing food purchases, perceived low availability, lack of marketing and information, lack of trust in the labelling system, and low perceived consumer effectiveness.
- Although CF labelling of food in a retail setting has limited effectiveness, CF values are important in business-to-business communication, in the development of tools and strategies for reduced emissions, in designing more powerful regulations and policy instruments and in developing effective and scientifically justified consumer communication messages for reduced GHG emissions from food consumption.
- CF calculations show that the recommendations to ‘eat less meat’, and to ‘waste less food’ are highly valid, while the recommendation to ‘eat local/seasonal/organic’ is less significant for reductions in GHG emissions considering the current food system in the developed world. In addition, the terms ‘local’ and ‘seasonal’ lack established definitions, which adds to the difficulty in drawing general conclusions.
- By consuming tomatoes and carrots seasonally in Sweden, according to four different definitions, the CF from their consumption can be reduced by 30-60%. This is a substantial reduction in relative terms, but only corresponds to emissions of 3-5 kg of CO_2e per capita and year, which is minor taking the GHG emissions from a complete average diet into account.

- When communicating the sustainability of different food products, several environmental and social aspects need to be considered. At the same time, information has to be simple, salient, credible and legitimate. Developing such communications is highly challenging, as exemplified by the ‘meat guide’ for the Swedish market. More research on communicating LCA results to consumers and other stakeholders is urgently needed.

6.2 Implications and perspectives

The scope of this thesis is wide, which is inevitable when trying to tie together both natural and social sciences, entering into the necessary detail and at the same time critically reflecting on the relevance and usability of the subject under study. Can the implications of the conclusions listed above be summarised in a few paragraphs? Well, labelling retail food packages with detailed numerical CF seems not to be worth the effort, since calculating CF values is difficult, costly and uncertain, and since CF information on food packages is ineffective in influencing consumers to change consumption patterns. However, calculating food CF as a whole has other values, as life cycle calculations, however uncertain, are necessary for designing communication messages, tools and policy that can influence consumer behaviour.

Food CF information is highly valuable in the design of future food systems and products in research, industry, retail and the public sector, and could be useful in consumer purchase situations where the number of products is limited. However, care should be taken to avoid problem shifting, especially as regards use of water and pesticides, impacts on biodiversity and animal welfare, when striving for decreased CF. More research is needed on calculating CF at a relevant level of precision in different situations and how to handle possible trade-offs. However, the risk of damaging other environmental areas and generating inaccuracies when calculating and acting on food CF must be weighed against the risk of not acting at all. Or as Weidema et al. (2008a) put it already in 2008:

> “…if decisions based on the indicator go in the right direction just 80% of the time, it will still be better to use this indicator than to use no environmental indicator at all.”

It is discouraging to conclude that CF labelling of food packages to enable active consumer purchasing choices, which started out as an industry initiative driven in many cases by a (probably) genuine will to reduce GHG emissions, is ineffective. However, the CF labelling process in itself has increased interest among food producers and the food industry in research and standardisation and has greatly increased awareness of the climate impact of food among food professionals and some consumer groups. This is highly valuable in itself, not least in order to pave the way for more powerful policy instruments.

More research is needed to devise effective communication strategies in the area of sustainable food consumption. Studies are needed on how consumers and other influential actors in the food chain use CF information when presented with possible environmental and social trade-offs, as well as taste and price criteria. In addition, the consumer cannot bear the whole environmental burden of food production, so all actors in the food sector must take responsibility to decrease emissions and reduce resource use from food consumption. The CF can play an important role as a sustainability indicator in internal work to reduce emissions and also when communicating with other businesses and interested consumers, either directly by actual numerical values, or by targeted symbols or messages that are easier to grasp.

Finally, GHG emissions from foods must be put in a wider perspective. In the developed world, emissions from the transport and energy sectors still dominate GHG emissions to a large extent. A car trip to the supermarket or local farm shop can emit substantially more than the production of the food products purchased. Turning vegetarian can potentially save 0.7 ton CO_2e per year which can be compared to one return trip from Europe to Asia of approximately 2 ton CO_2e. In fact, emissions from travel would need to come down close to zero to allow some unavoidable emissions from food production to achieve the yearly per capita sustainable level of 1 ton CO_2e. In this challenge there is an obvious need for the continued calculation of the life cycle CF for different activities and products, including foods, using improved methods.

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